FUNCTIONAL ANATOMY OF THE VERTEBRAL VASCULATURE IN REPTILES

By

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To the animals who give their lives in the name of science.

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Chairman: Harvey Lillywhite
Major Department: Zoology

The veins and arteries within and around the vertebral column are among the least studied blood vessels in tetrapods, probably as a result of their being ensconced within bone. Using vascular corrosion casting, I studied the anatomy of the vertebral and spinal arteries in rat snakes, and of the vertebral and spinal veins in snakes and crocodilians. I also used fluorescent microspheres and radiography to reveal patterns of blood flow through these vessels in intact animals under various experimental conditions.

Regional blood flow analyses revealed that the vertebral artery supplies about 13% of blood flow to the brain in rat snakes, the rest arriving through the carotids. The vertebral contribution is indirect, occurring through multiple anastomoses between the vertebral and spinal arteries in the neck.

Blood leaving the brain of snakes can follow two routes back to the heart. The jugular veins are well developed, but the veins of the vertebral column form a second system, previously undescribed in reptiles, called a vertebral venous plexus. Using fluoroscopy, I demonstrated that the jugulars receive venous return from the head in horizontal animals, but the plexus adopts this role during upright posture. The jugulars are compliant and collapse under the gravitational stress of upright posture, but the vertebral veins, with the structural support of the surrounding bone, remain patent with negative intraluminal pressure anteriorly. Consequently, passage of blood into the plexus conceivably facilitates perfusion by providing a low-pressure route for cerebral efflux, thereby driving up the perfusion gradient across the brain.

In crocodilians, the spinal veins form a voluminous ‘sinus’ dorsal to the spinal cord, similar to that of birds. I demonstrated that this vessel plays a major role as a collateral route of venous return to the heart. In both these groups, the spinal vein forms a supraspinous groove on the dorsal surface of the neural canal. I used the Extant Phylogenetic Bracket technique to test the hypothesis that the relationship between the bone and blood vessel in these two groups is homologous, allowing me to infer that dinosaurs also possessed a robust spinal vein and enjoyed similar posture-induced benefits.

CHAPTER 1
INTRODUCTION

This work explores certain aspects of structure and function of the vertebro-spinal vasculature in reptiles. The base of our current knowledge regarding reptilian vascular anatomy stems from research conducted in the late eighteenth, the nineteenth, and the early twentieth centuries. During that period, the available techniques were crude and simple, consisting primarily of gross dissection of cadavers, usually after the injection of various dyes and/or gelatin into the primary blood vessels (e.g., the works of Rathke and Beddard, reviewed in subsequent chapters). Due to difficulty of access, the vessels ensconced within the bony vertebral column were essentially ignored. In the mid- to late twentieth century, new techniques were developed, primarily in the medical field, to facilitate studies of structure and function of the vascular system. For purposes of descriptive anatomy, dye/gelatin injection was replaced with corrosion casting, which allowed three-dimensional visualization and dissection of the entire vascular system independent of the other body tissues (e.g., Lametschwandtner et al., 1984). Angiography allowed direct observation of hemodynamics in living animals (e.g., Lake et al., 1990), and microsphere analysis permitted the quantification of blood flow to specific organs and tissues (e.g., Rudolph and Heymann, 1967). Herein, I use these techniques to examine the functional morphology of the blood vessels associated with the reptilian vertebral column.

Chapter 2 is an investigation into the role of the vertebral artery in supplying blood to the head of snakes. In all tetrapods, cerebral perfusion occurs primarily through the carotid arteries. However, the vertebral arteries of mammals are known to supplement the carotid artery contribution to the brain by way of the basilar artery and the Circle of Willis. In other tetrapods, the role of the vertebral arteries is less clearly understood: they are almost invariably described as disappearing into the dorsal musculature along the vertebral column between the heart and head. I chose to examine the anatomy and hemodynamics of the vertebral artery in the rat snake, *Elaphe obsoleta*. To test the hypothesis that the serpentine vertebral artery also contributes to cerebral circulation, I employed fluorescently labeled microspheres. This analysis allowed me to quantify and compare the contributions of the vertebral and carotid arteries to cerebral perfusion. I then used vascular casting to reveal the branches, connections, and terminations of the vertebral artery. Finally, I used fluoroscopy to observe patterns and directions of blood flow in the cervico-cephalic vasculature. The material in Chapter 2 is also available in the Journal of Morphology (Zippel et al., 1998).

Chapter 3 examines the role of spinal veins as a collateral route of venous return from the head in snakes. Although spinal veins appear to be a feature common to all vertebrates, an extensive plexiform arrangement with a major role in cerebral circulation has previously been documented only in mammals. I used corrosion casting and histology to demonstrate and describe the spinal veins as they occur in eight snake species representing seven genera in three families. To test the hypothesis that gravity affects circulation in vertical circuits, I then used fluoroscopy to observe the effects of posture on venous return from the head in two snake species.

Chapter 4 addresses the siphon controversy, an ongoing debate regarding energy expenditure in vertical blood circuits and whether cerebral blood supply is facilitated by the nature of venous return. Here, I re-examined this issue in light of the knowledge that cerebral efflux in certain upright animals passes largely into the spinal veins. I also reviewed and reevaluated the role of cerebrospinal fluid in facilitating cerebral perfusion.

Chapter 5 examines the structure and function of the spinal veins in crocodilians. This system was essentially unknown, and knowledge of the spinal veins in extant archosaurs allows meaningful inference about circulatory patterns in upright dinosaurs. Using vascular casting, I compared the morphology of the spinal veins in crocodilians to those of birds and other vertebrates. To test the effect of various environmental conditions on circulatory patterns in the spinal vein, I fluoroscopically examined the hemodynamics within the spinal veins of alligators in air, submerged in water, and exposed to a radiant heat source from above. Finally, I examined skeletal material from extant and extinct archosaurs to make inferences about vascular anatomy and function in dinosaurs.

Chapter 6 is a summary of all the significant findings and conclusions from previous chapters and includes prospects for future investigation on this topic.

CHAPTER 2
CONTRIBUTION OF THE VERTEBRAL ARTERY TO CEREBRAL CIRCULATION IN THE RAT SNAKE *ELAPHE OBSOLETA*.

Background

General

Maintenance of blood flow to the brain is the most vital task of the vertebrate circulation (Rowell, 1993). Although many studies have focused on the importance of cerebral blood supply, there have been relatively few descriptive accounts of patterns of flow in the associated cervical and cephalic vasculature, especially in non-mammalian vertebrates. Cephalic hemodynamics are of particular interest in very large or upright species, which are susceptible to gravitational stresses induced by posture. Among reptiles, arboreal snakes posses both structural and physiological adaptations to maintain circulation in vertical blood columns (Lillywhite, 1987; Lillywhite and Donald, 1994). Although cardiovascular responses to upright posture have been well studied in snakes, little is known concerning structure and function of the vasculature that services the brain. In general, studies of reptilian circulation have emphasized cardiac anatomy and shunting, while other aspects of vascular hemodynamics remain poorly understood.

Blood supply to the brain of vertebrates is achieved primarily through the carotid vasculature. In mammals, cerebral perfusion is supplemented by the vertebral arteries, which anastomose with the carotids at the base of the brain. In other tetrapods, the vertebrals are usually described as passing into the dorsal musculature between the heart and head, with no further mention of their ultimate terminations (e.g., Walker and Homberger, 1992). Although, there have been several reports of a vertebral artery connection with the brain in snakes (see below), the hemodynamics in the intervening vasculature is unknown. Herein I describe the vertebral artery of a colubrid snake with arboreal tendencies, *Elaphe obsoleta quadrivittata*, which I chose because of its scansorial behavior and known hemodynamic responses to upright posture (Lillywhite and Gallagher, 1985). My purpose is to describe the anatomy in relation to its possible contribution to cerebral perfusion. I then combine this analysis with the results from physiological studies using fluorescent microspheres and demonstrate for the first time a small but significant contribution of the vertebral artery to cerebral blood flow in a reptile. Finally, I elucidate the pathway of flow via indirect vascular anastomoses, and I relate these new findings to patterns of vertebral flow in other vertebrates.

Anatomy of the Vertebral Artery

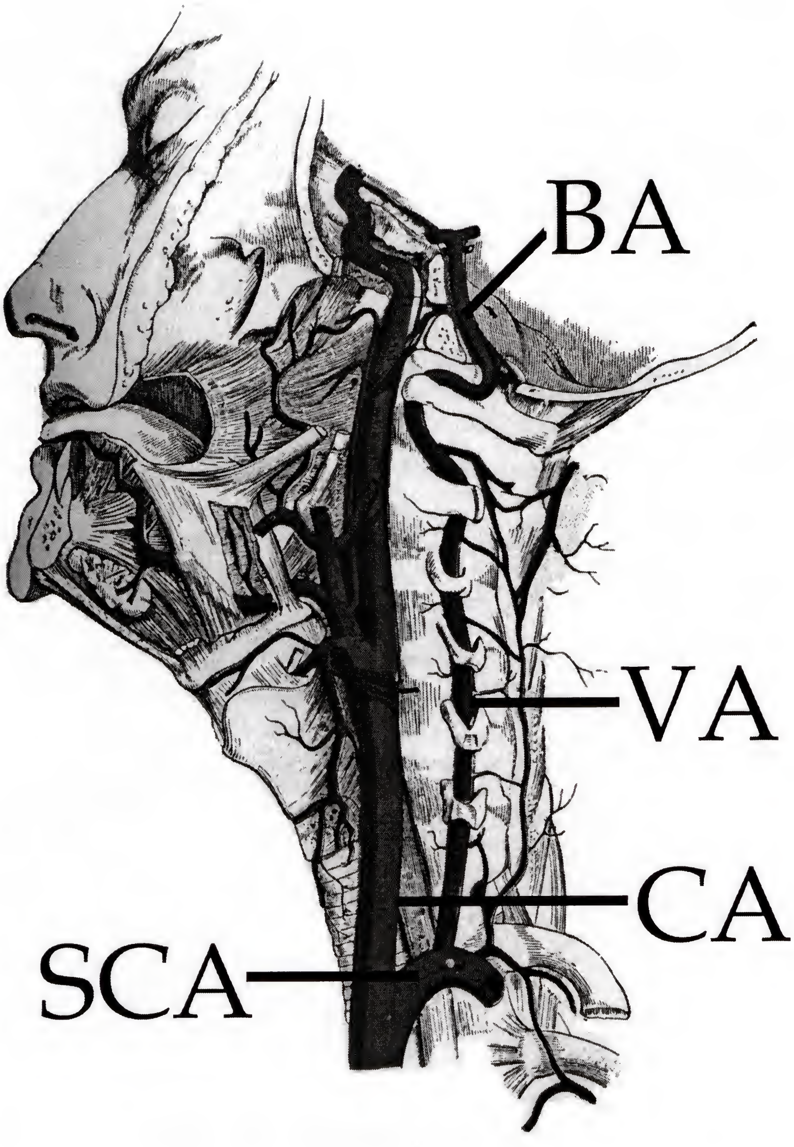
Although a vertebral artery is present in all tetrapods, its anatomical pathway is best understood in mammals (Gray, 1995). The paired vertebrals in mammals arise as branches of the subclavian arteries and each enters a lateral canal in the cervical vertebrae (Fig. 2.1). From there the vertebrals course into the head where they unite at the base of the brain and continue to flow anteriorly as the basilar artery. The basilar in turn connects with the carotid arteries forming the Circle of Willis on the ventral surface of the brain. Numerous smaller arteries that radiate from the Circle supply blood to the cerebrum and surrounding tissues. The vertebral arteries in humans, in which the anatomy is best studied, produce numerous branches in the neck and head. Several of the cervical branches enter the spinal canal and anastomose directly with the spinal arteries. Within the cranium, the vertebral arteries send several branches to the cerebellum and medulla directly before uniting as the basilar artery. Several posteriorly directed extensions of the basilar and vertebrals, the spinal arteries, supply the spinal cord and associated tissues along the length of the vertebral column.

The intracranial vascular arrangement is somewhat more complicated in those ungulates and carnivores that possess a carotid rete (Daniel et al., 1953). In these groups, the basilar/vertebral connection is weak or absent, and vertebral blood does not usually contribute to cerebral supply (Andersson and Jewell, 1956; Baldwin and Bell, 1963a). However, some species possess alternative connections between the vertebral and carotid vasculature (e.g., a basioccipital plexus and/or an occipitovertebral anastomosis) and a vertebral contribution still exists (Goetz and Keen, 1957; Baldwin and Bell, 1963a).

In non-mammalian tetrapods, the path of the vertebral arteries is less clearly understood. The vertebrals typically arise as a branch of the subclavian artery, the carotids, or directly from the ascending aorta, and are typically described as disappearing into the dorsal musculature between the heart and head (e.g., Walker and Homberger, 1992).

The ancestral condition of vertebral arteries in squamate reptiles, as typified in lizards, consists of paired vessels (Rathke, 1857). As in mammals, these vessels arise from the subclavians and course anteriorly adjacent to the vertebral column. Along their route, the vertebrals give rise to numerous branches, the intercostal arteries, which supply the parietes of the dorsum. Rathke (1857) followed the lateral branches of the

FIGURE 2.1. Diagram of the vertebral artery and its connectives in a human (modified from Gray, 1995). BA, basilar artery; CA, carotid artery; SCA, subclavian artery; VA, vertebral artery.


BA
VA
CA
SCA

intercostals in a lizard and implied that they are sent into the vertebral canal to join the spinal artery, a condition reminiscent of that seen in the cervical region of mammals. The vertebrals proceed as far forward as the atlas, but are almost never reported to enter the head. A single account (Beddard, 1905a) stated that the paired vertebral arteries in "Lacertilia" behave exactly as in mammals, entering the head before fusing and giving rise to the basilar and spinal arteries at the base of the brain.

There appears to be a gradual transition in the configuration of the vertebral artery from the primitive, paired arrangement in quadrupedal lizards to the derived, single form in some elongate and legless reptiles (Rathke, 1857). In amphisbaenians, the ancestral arrangement is maintained, but in snakes and certain legless lizards, consistent with other reductions for elongation, only a single vertebral artery persists. In snakes, this vessel gives off up to 30 intercostals and may send branches to the trachea, esophagus, or pharynx in some species before ultimately coursing into the dorsal musculature (Beddard, 1904a; Thompson, 1914; Kashyap and Velankar, 1958). Heyder (1973) made serial sections of the neck of *Typhlops vermicularis* to reveal the disappearing vertebral and found that it continued further anteriorly in a right foramen transversarium, similar to that seen in mammals, as far as the first cervical vertebra. Beddard (1905a) examined *Python molurus* and claimed that, as he saw in lizards, the vertebral arteries (apparently two) unite with the basilar and spinal arteries at the base of the brain. Given that he apparently observed paired vessels, and given the location of their connection in his illustration, I believe that Beddard had mistaken the right and left first spinal arteries for the vertebrals. The first spinals unite to form an anastomosis between the left and right carotid arteries at the base of the skull. Recall that the right carotid artery between the heart and neck is lost in advanced snakes, and the cephalic remnants of the right are fed by this anastomosis with the left. I must therefore also question whether he mistook the spinal arteries for a direct vertebral connection in lizards as well (see above).

The most detailed analyses of vertebral artery configuration in snakes have been conducted on vipers. Van Bourgondien and Bothner (1969) examined the arterial systems in ten species (four genera) of viperids, and their findings are reviewed briefly here. After the vertebral artery passes into the dorsal musculature it divides into cranial and caudal branches. The cranial branch continues its anterior route, giving off one pair of intercostal arteries per vertebra. As in mammals, some of these branches enter the vertebral column to supply the inferior spinal artery. The ascending cranial branch of the vertebral extends to the base of the skull, where it is met by a descending branch (the cervical artery) from the left side of the carotid anastomosis. This connection is always robust in viperids, and occasionally a branch arises here to meet the descending cervical artery from the right side of the anastomosis as well. The inferior spinal artery arises medially from the carotid anastomosis, between the right and left cervical arteries. An anterior extension of the inferior spinal, the basilar artery, continues ventral to the brain where it anastomoses anteriorly with branches of the internal carotids.

Lillywhite (1993a) also cast the vertebral artery of a viper and traced its branches into the vertebral column. Latex exited the column anteriorly in vascular connectives associated with the cephalic carotid vasculature, and latex was present in the facial tissues. However, the extent of the vertebral contribution to the head, as evidenced by the degree of latex perfusion, appeared "at best small and probably insignificant." Gillian (1967), in a comprehensive survey of cerebral blood supply in "submammalian" vertebrates, declared that the basilar and spinal arteries in these groups are simply extensions of the caudal rami of the internal carotids and receive no vertebral contribution. Gillian (1967), Hasegawa and Kubo (1966), and Iijima et al. (1977) examined cephalic vasculature in colubrid snakes, but did not describe connections from the vertebral artery.

Materials And Methods

Adult yellow rat snakes (*Elaphe obsoleta quadrivittata*) of mixed sexes were shipped by air from a supplier in central Florida and maintained in the laboratory for several weeks prior to use. Snakes were kept on newspaper in fiberglass cages with *ad libitum* access to water and were fed mice weekly. Acclimation air temperatures were maintained between 24 and 26°C. The Institutional Animal Care and Use Committees of the NASA Ames Research Center and the University of Florida approved all research on these animals.

To quantify regional blood flow values from the cervical arteries, 13 snakes [117 ± 14 cm SVL (snout-vent length); 510 ± 182 g body mass; means ± standard deviation] were subjected to microsphere injection and analysis. These animals were administered 40 mg/kg sodium pentobarbital (Veterinary Laboratories, Inc., Lenexa, KS) intramuscularly and given at least 1 h to reach a surgical plane of anesthesia. After loss of a righting response and voluntary movement, snakes were tested for pain response by pulling or pinching the tongue, which remained sensitive long after other methods indicated the animal was insensate. Once anesthetized, each snake was prepared surgically on chipped ice, not as part of anesthesia (as was done in the past and has since been deemed inhumane), but simply to minimize bleeding. I employed several procedures for delivery of microspheres, including injection of small volumes directly into the vertebral or carotid artery to minimize disturbance of hemodynamics (see Table 2.1). For comparisons of vertebral and carotid contributions to cerebral blood flow within individuals, the standard protocol was to inject microspheres of different fluorescent label sequentially into the carotid and vertebral artery, or vice versa. In a similar study, where blood samples were withdrawn from superior and inferior vena cava over a period of several minutes following microsphere injection, recirculation of microspheres was demonstrated to be negligible (Lillywhite and Gallagher, 1985).

To prepare snakes for injection of microspheres, I made an incision approximately 5 cm posterior to the heart and both the distal right aorta and the pulmonary vein were isolated and cannulated with polyethylene (PE-10) tubing (Becton Dickinson and Co., Parsippany, NJ). Cannulation of the vein was non-occlusive. A second incision of several cm was made along the left edge of the ventral scutes immediately anterior to the heart, allowing access to the carotid and vertebral arteries. Prior to microsphere injection, snakes were primed with an intravenous injection of 100 μl 0.05 % Tween 80 (Fisher Scientific Co., Pittsburgh, PA), which is present in the microsphere suspension to prevent clumping. Millard et al. (1977) have shown that an initial injection of Tween 80 can cause such cardiovascular disturbances as reductions in cardiac dimensions, hypotension, and tachycardia. However, priming conditions the vasculature to the presence of Tween 80, and thereby avoids repeated disturbance during subsequent injections that day (Millard et al., 1977). The vertebral artery was then clamped at its proximal base and a 100 μl suspension (5×10^5 spheres) of NuFlow™ violet-high fluorescent-labeled

TABLE 2.1. Whole-body and tissue measurements for rat snakes, *Elaphe obsoleta,* in the microsphere analysis.

	snake mass (g)	reference[a] blood 1 (ml)	reference blood 2 (ml)	brain mass (g)	tongue mass (g)	collection time (sec)	injection/collection sites[b]
	278	1.95	-	0.14	0.05	300	into PVC, from aorta
	409	1.34	-	0.07	0.05	300	into PVC, from LAA
	550	1.88	-	0.13	-	300	into PV, from DA
	435	-	-	0.18	-	300	directly into VA, no ref. flow
	668	0.51	-	0.24	-	300	into PV, from RAA
	524	0.56	-	0.23	0.11	210	into PV, from RAA
	236	-	-	0.13	-	300	directly into CA, no ref. flow
	915	1.16	1.06	0.24	0.09	300	into PV, from RAA
	654	1.30	1.28	0.24	0.10	300	into PV, from RAA
	597	0.43	0.74	0.18	0.08	300	into PV, from RAA
	575	0.99	1.07	0.21	0.07	300	into PV, from RAA
	362	1.34	1.53	0.20	0.06	300	into PV, from RAA
	430	0.67	0.74	0.17	0.06	300	into PV, from RAA
mean:	510	1.02	0.96	0.19	0.07		
s.d.	182	0.58	0.41	0.05	0.02		

[a] reference blood samples are drawn for the calculation of regional blood flows (see text).

[b] PVC, posterior vena cava; LAA, left aortic arch; PV, pulmonary vein; DA, dorsal aorta; VA, vertebral artery; RAA, right aortic arch; CA, carotid artery.

microspheres (Triton Technologies, Inc., San Diego, CA) was injected slowly into the pulmonary vein, followed by a 200 μl saline flush over a period of 1.5 - 2 min. A single reference blood sample (usually ca. 1 ml) was collected drop-wise from the open end of the right arch cannula for 5 min beginning 15 - 30 s before injection of the microspheres. The vertebral artery was then freed and the proximal carotid artery was clamped. The injection procedure was then repeated using a 100-μl suspension of red-high microspheres. Following collection of the second reference blood sample, the snake was administered a lethal overdose of pentobarbital. I then removed the brain and tongue and stored all tissues in vials at 5°C.

All tissue samples were subsequently analyzed by Interactive Medical Technologies, Ltd. (Santa Monica, CA). Tissues were digested via alkaline hydrolysis to recover the microspheres, which were then counted using flow cytometry. Color of the fluorescent label was distinguished by intensity values, as each color type has a unique fluorescent signature. Regional blood flow ($ml \cdot min^{-1} \cdot g^{-1}$) was calculated as the product:

$$\frac{TTS}{TM} \bullet \frac{WR}{TRS}$$

where TTS = the total number of spheres recovered from the tissue, TM = the mass of the tissue being analyzed (g), WR = the rate of withdrawal of the reference blood sample (ml/min), and TRS = the total number of spheres recovered from the reference blood sample.

Two snakes received direct injections of microspheres, one into the vertebral artery and the other into the carotid artery, without cannulation. Regional blood flow values were not calculated for these animals because I did not collect reference blood samples. The purpose of these injections was to test qualitatively for arterial contributions to cerebral circulation in the absence of vessel ligations, which could conceivably alter hemodynamics in the unclamped vessel.

To study the arterial anatomy, I employed vascular or corrosion casting. Eight rat snakes (115 ± 11 cm SVL; 460 ± 125 g body mass; means ± standard deviation) were anesthetized as above. The carotid artery, vertebral artery, jugular veins, and vertebral vein were isolated and cannulated with PE 50 tubing. The arterial cannulae were attached to syringes, and the venous cannulae were left open as drains. The anterior vasculature was then perfused at room temperature (23 ± 3°C) with heparinized (200 IU/ml) 0.9 % saline through the arterial cannulae until the reflux drained clear. In general, this required about 20 ml of saline administered over 10 min at a pressure sufficient to distend the vessels to their pre-cannulation capacity. Following saline perfusion, snakes were euthanized as above. A mixture of Mercox resin and catalyst (75:1 by volume, ca. 5 ml total; Ladd Research Industries, Inc., Burlington, VT) was then perfused through the anterior vasculature until it appeared in the venous drains. All vessels were then ligated to prevent back-pressure drainage.

To cure the Mercox cast and soften the flesh, the specimen was soaked in a water bath at room temperature overnight. Soft tissues were then digested in a 10% NaOH solution (ca. 40x the specimen volume), and the bones were decalcified in 5% HCl. The remaining organic material was removed in 5-10% commercial chlorine bleach or 10% NaOH, sometimes in conjunction with an ultrasonic cleaner (Branson Cleaning Equipment Co., Shelton, CT), thus leaving the intact vascular cast. Further cleaning of the casts (e.g., removal of superficial capillary-bed casting) was done manually with dissecting scissors and forceps. Casts were allowed to air dry and were stored in plastic containers.

I then used fluoroscopy to visualize patterns of arterial blood flow. Two rat snakes (127 ± 0 cm SVL; 585 ± 46 g body mass) were induced with 5% isoflurane gas (AErrane®; Anaquest, Madison, WI) in an anesthesia chamber and maintained with oxygen and 1 - 3% isoflurane gas via an endotracheal tube. A sterile field was prepared, and the vertebral artery was isolated and cannulated with PE 10 tubing. The cannulae were considerably smaller than the vessels and were glued to the vessel at the site of penetration, then sutured to the body wall, rather than being ligated directly around the vessel. Consequently, the cannulation was essentially non-occlusive and permitted blood flow past the cannulation site. The incisions were closed in a sterile manner, and the animals allowed to recover for several days. Snakes were administered 5 mg/kg enrofloxacin (Baytril®; Shawnee Mission, KS) after surgery and every 48 hours thereafter for six days. Cannulae were kept patent by manual flushing every few hours and capped when not in use. Snakes were restrained in transparent acrylic tubes slightly larger than their girth, and injections of iodinated contrast medium, iohexol (Omnipaque 350®; Nycomed Inc., Princeton, NJ), were then administered in sufficient quantity to visualize patterns of blood flow on a C-arm digital subtraction fluoroscope (OEC-1; OEC Diagnostics, Salt Lake, UT).

One rat snake (127 cm SVL; 552 g body mass) from the angiography experiment was anesthetized with sodium pentobarbital as above. To expose the vessels encased within the vertebral column, I used a miniature rotary tool to open the centra of three consecutive vertebrae between the heart and head. The spinal cord was reflected to permit direct observation of the columnar vessels, e.g., the spinal artery and veins. A 100-μl bolus of green food coloring was introduced into the vertebral artery cannula to aid in visualizing the direction of flow in the spinal artery.

Results

Microsphere Analysis

The mean cerebral blood flow from the vertebral artery was 0.208 ± 0.156 ml/min/g (N=9), just 16% of that from the carotid artery, 1.338 ± 1.316 ml/min/g (N=8) (Table 2.2). In all six snakes where both carotid and vertebral contributions were measured, flow from the vertebral was consistently a fraction of that from the carotid (9.6 to 28.4%). The differences between the cerebral contributions of these two vessels are statistically significant (Wilcoxon signed-rank test, two-tailed: p=0.025).

In the two snakes that received direct injections of microspheres without cannulation, one into the vertebral and the other into the carotid artery, regional blood flow values were not calculated, as no reference blood samples were collected. Nevertheless, microspheres were retrieved from the brain tissue in both cases.

Both the carotid and vertebral arteries also supply blood to the tongue (Table 2.2). The mean vertebral contribution, 0.119 ± 0.102 ml/min/g (N=7), was 7% of that from the carotid, 1.780 ± 2.927 ml/min/g (N=8). In the six snakes where both carotid and vertebral contributions were measured, the flow from the vertebral varied from 3.8 to 101.9% of that from the carotid; differences were not statistically significant (Wilcoxon signed-rank test, two-tailed: p>0.05).

TABLE 2.2. Regional blood flow values from carotid and vertebral arteries, measured sequentially in cephalic tissues of anesthetized rat snakes, *Elaphe obsoleta*. Data are means ± standard deviation.

tissue	mass (g)	rate of blood flow ($ml \bullet min^{-1} \bullet g^{-1}$)	
		carotid artery	vertebral artery
brain	0.19 ± 0.05	1.338 ± 1.316	0.208 ± 0.156
tongue	0.07 ± 0.02	1.780 ± 2.927	0.119 ± 0.102

Vascular Casts

Vascular casts revealed the path of the vertebral artery between the heart and head. The vertebral arises directly from the ascending right aorta distal to the origin of the carotid (Fig. 2.2). It courses anteriorly along the vertebral column in a retroperitoneal position. At a point about midway between the heart and head, the vertebral passes medially into the dorsal musculature and proceeds anteriorly alongside the vertebral column in a groove created by the hypapophyses ventrally and the parapophysial processes dorsally (Fig. 2.3). No caudal branch was observed. Every 1-4 segments, the vertebral artery produces an intercostal branch, which irrigates the dorsal parietes and enters the vertebral column to anastomose with the inferior spinal artery (Fig. 2.4). The vertebral attenuates as it proceeds anteriorly, and terminates near the 15th vertebra (Fig. 2.5). The spinal artery continues forward to meet the internal carotid anastomosis at the base of the skull (Fig. 2.6). The basilar artery, initially bifurcated, extends anteriorly beneath the brain from this junction. Extending posteriorly along either side of the spinal artery are two cervical branches of the internal carotid anastomosis. These cervical arteries also attenuate by the 15th vertebra (Fig. 2.5), and thus no direct connection between the vertebral artery and the carotid anastomosis was observed.

Fluoroscopy

Fluoroscopy in conscious snakes allowed direct visualization of fluid movement from the vertebral artery into the spinal artery through the multiple anastomoses described above. From this point in the spinal artery, the fluid was seen to move anteriorly into the carotid vasculature of the head (Fig. 2.7).

Direct Observation

The spinal artery is intimately associated with the spinal cord, such that dissection and reflection of the cord necessarily severed the artery, although the underlying veins remained undamaged. Filling of the resultant cavity (vacated by the cord and artery) could be observed to occur from the posterior end. The food coloring injected into the vertebral artery cannula appeared in the spinal cavity within seconds and flowed anteriorly.

Discussion

Blood supplying the brain in most vertebrates is carried exclusively by the internal carotid arteries. There are three known exceptions, one of supplantation and two of supplementation. The first involves a case of "stream piracy" by the external carotid arteries. The external carotids begin embryonically in all vertebrates as diminutive vessels supplying blood to the lower jaw and associated structures. The larger internal carotids supply the brain, face, and jaws. This condition is maintained ontogenetically in all but the advanced mammals, where each external carotid expands, taps into the stapedial artery (a major branch of the internal carotid), and assumes the task of supplying the face, jaws, and meninges. This process has gone so far in certain carnivores, ungulates, and cetaceans (and as a pathologic condition in some humans; Gray, 1995) that the connection between the internal carotids and the brain is lost, and

FIGURE 2.2. *Elaphe obsoleta.* Vascular cast (full maceration) of the heart and primary vessels. Ventro-lateral view, anterior to the left, left auricle removed. DA, dorsal aorta; LAA, left aortic arch; LCA, left carotid artery; PVC, posterior vena cava; RAA, right aortic arch; V, ventricle; VA, vertebral artery; VV, vertebral vein.

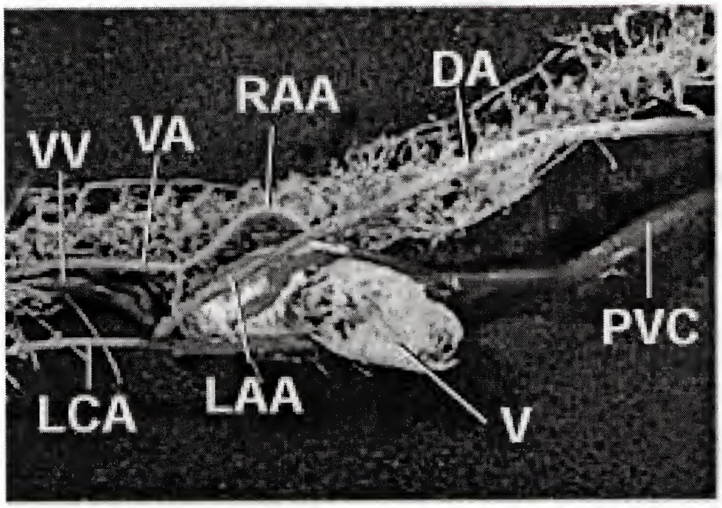

DA
RAA
VV
VA
PVC
LCA
LAA
V

FIGURE 2.3. *Elaphe obsoleta*. Vascular cast (muscle maceration only) of the vertebral artery coursing anteriorly between the hypapophyses and the parapophysial processes. Lateral view, anterior to the left. H, hypapophysis; IA, intercostal artery; PP, parapophysial process; VA, vertebral artery.

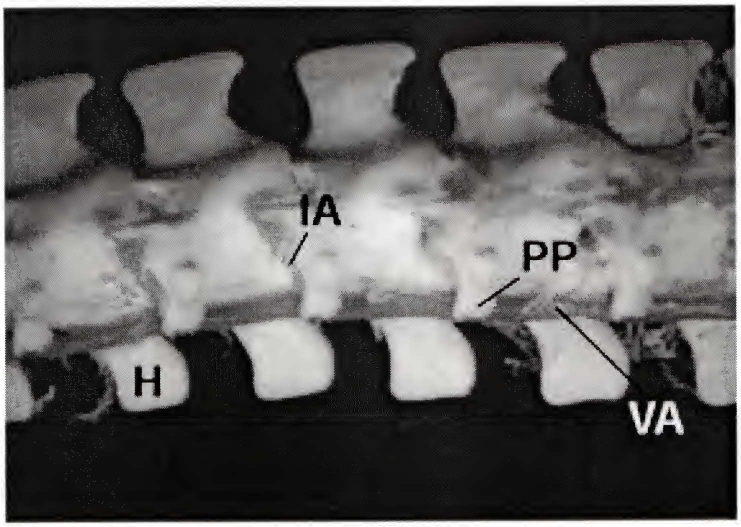

IA
PP
H
VA

FIGURE 2.4. *Elaphe obsoleta.* Vascular cast (maceration of muscle, some bone) revealing anastomoses between the vertebral and spinal arteries, via the intercostal arteries. Ventro-lateral view, anterior to the left. IA, intercostal artery; SA, spinal artery; VA, vertebral artery.

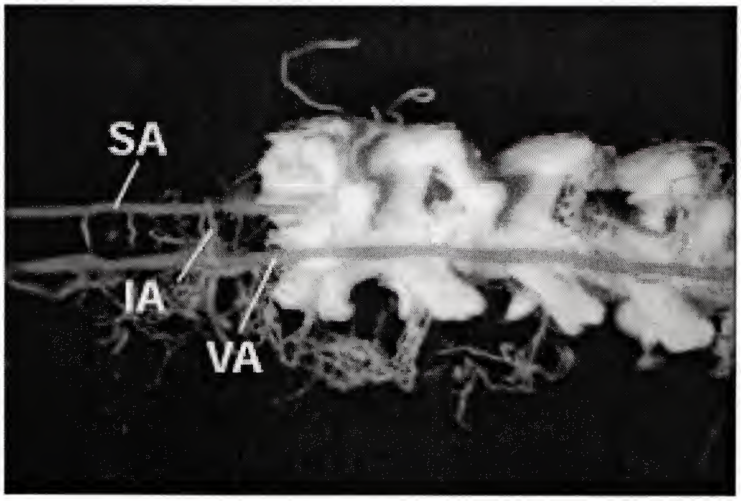

SA
IA
VA

FIGURE 2.5. *Elaphe obsoleta.* Vascular cast (full maceration) showing attenuating vertebral artery at the level of the 15th vertebra and its proximity to the branch from the carotid anastomosis. Lateral view, anterior to the left. B, branch from the carotid anastomosis; SA, spinal artery; VA, vertebral artery.

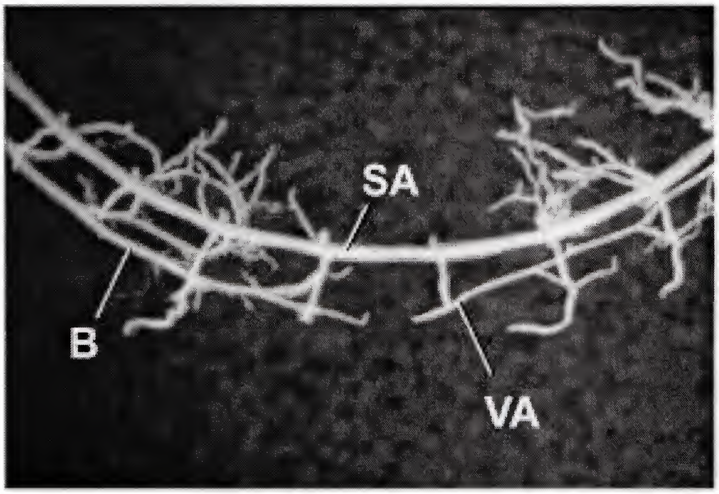

SA
B
VA

FIGURE 2.6. *Elaphe obsoleta*. Vascular cast (full maceration) revealing the cephalic vessels. Ventral view, anterior to the left. B, branch from the carotid anastomosis; BA, basilar artery; CA, carotid anastomosis; LCA, left carotid artery; RCA, right carotid artery; SA, spinal artery.

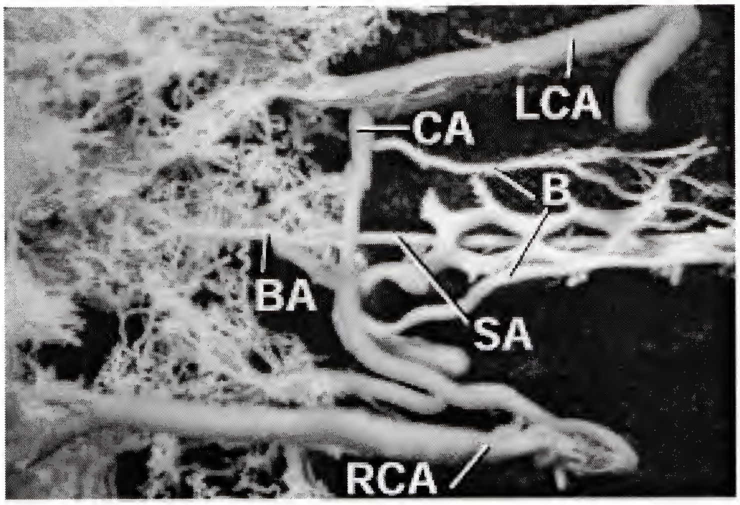
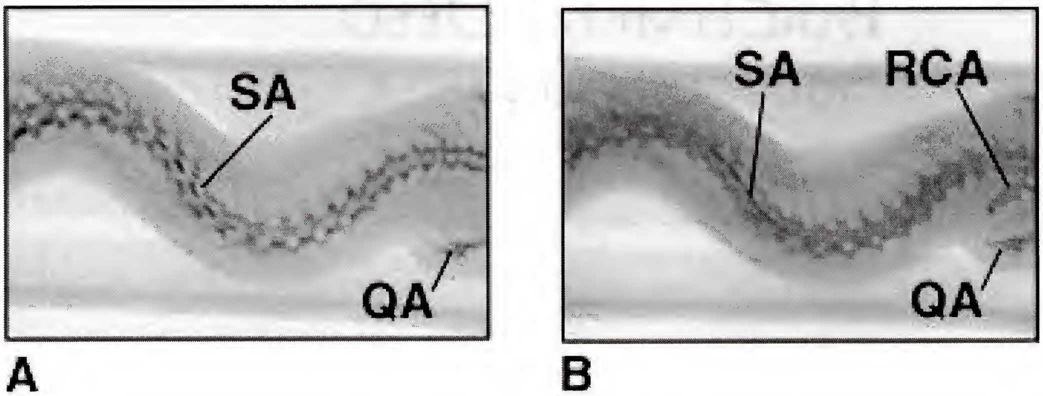

LCA
CA
B
BA
SA
RCA

FIGURE 2.7. *Elaphe obsoleta*. Fluoroscopic image of traveling Iohexol bolus. **A**: Bolus has passed from vertebral artery into spinal artery. **B**: Bolus has passed into carotid vasculature of the head. QA, quadratomandibular articulation (for reference); RCA, right carotid artery; SA, spinal artery.


SA
QA
A
SA
RCA
QA
B

carotid blood reaches the brain only through the external carotids (Daniel et al., 1953; Melnikov, 1997).

In the other two cases, a second unrelated vessel supplements the flow from the internal carotids. In cartilaginous and a few bony fishes, the efferent pseudobranchial (spiracular) artery (derived from Arch II efferent) passes from the spiracle into the braincase to connect with the internal carotids (derived from Arch III and anterior dorsal aorta) beneath the brain, supplying this organ and the eye with blood (Romer and Parsons, 1986). In most mammals, the vertebral arteries (derived from dorsal aorta and possibly Arch IV) supply the spinal cord, brain stem, and cerebellum before merging with the carotids to irrigate the cerebrum (Gray, 1995). In these two cases, the redundant or collateral circulation is thought to help equalize blood pressure at the brain and/or provide an alternate course of flow should one system become impaired (Gray, 1995).

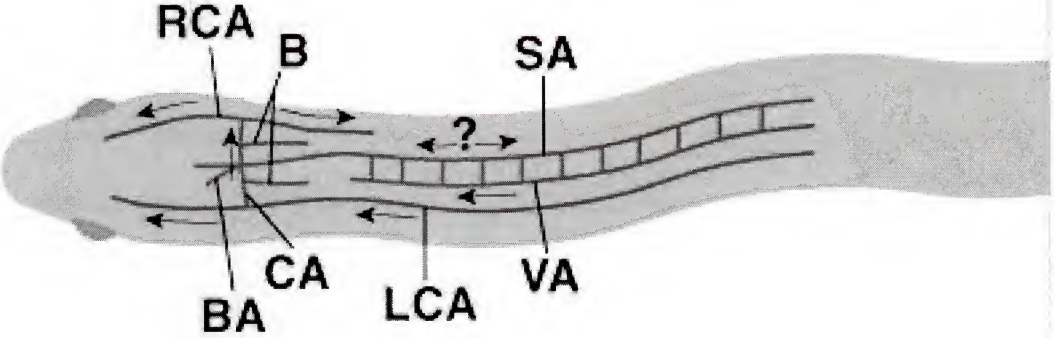
In all other vertebrates, cerebral blood is generally believed to be supplied exclusively by the internal carotid arteries. Gillian (1967), in a comprehensive survey of cerebral blood supply in "submammalian" vertebrates, declared that cerebral irrigation in these groups occurs entirely through the carotid vasculature. Further, she stated that the basilar/spinal arteries are formed and fed solely by the caudal rami of the internal carotids, not by the vertebral arteries as in mammals. Gillian mentions another vessel possibly related to cranial circulation in snakes: "The snakes are the only submammals to receive a substantial potential contribution to the circulation of the brainstem at the lower end of the basilar artery through the artery of the first cervical nerve. This is not a vertebral artery, because the latter has not yet developed phylogenetically." It is unclear whether her artery of the first cervical nerve is equivalent to the vertebral artery of other authors and her distinction is simply one of homology. In humans, the vertebral artery is indeed intimately associated with the first cervical nerve (the suboccipital) as they exit the vertebral column in the region of the atlas (Gray, 1995). However, as Gillian's vessel is apparently considered a carotid derivative and is paired, it is probably not comparable to the vertebral artery of other authors. More likely, the vessel to which she referred is simply the internal carotid anastomosis, described in more detail by Van Bourgondien and Bothner (1969) as the first spinal arteries. The latter investigators clearly detailed the anatomical pathway of the vertebral artery in viperid snakes and thereby revealed a direct cephalic connection. However, they could only speculate on the direction of blood flow and which vessel supplied which: the confluence of the left carotid artery and vertebral artery "provides an adequate blood supply to the right internal carotid artery, as well as feeding the right and left basilar arteries rostrally, and caudally the inferior spinal artery."

My analysis of regional blood flows in the rat snake, *Elaphe obsoleta,* provides a third example of cerebral supplementation, similar to that seen in mammals. Although the carotid artery clearly supplies the majority of blood flow to the brain, the vertebral artery also contributes a significant fraction of the total cerebral perfusion, potentially about 13% (Table 2.2). There is a similar division of blood contributions from these two arteries in the tongue (Table 2.2). My absolute values for cerebral blood flow are approximately three-fold higher and more variable than those reported earlier by Lillywhite and Gallagher (1985), who used radio-labeled microspheres in fully conscious rat snakes. These differences possibly reflect the effects of anesthesia and/or differences in the analytical procedure. That clamping a vessel, specifically a carotid or vertebral artery, inflates values of blood flow in collateral vessels is well documented (Baldwin and Bell, 1963b,c). Blood that would have coursed into the clamped vessel is presumably redirected into the adjacent vasculature, thereby inflating blood flow values in those vessels. However, my combination of protocols for injection and retrieval of microspheres into the cervico-cephalic circulation clearly indicate a vertebral contribution to cerebral blood flow that is comparatively small in relative magnitude. Percentages for cerebral contribution from the vertebral artery in primates are approximately twice as great (macaques, 30%: Dumke and Schmidt, 1943; human infant, 31%; adult, 24%: Schöning and Hartig, 1996).

Vascular casts revealed that the vertebral artery connection is indirect, through multiple anastomoses between the intercostal branches of the vertebral artery and the inferior spinal artery. No direct connection between the vertebral and carotid arteries was observed as in viperids (Van Bourgondien and Bothner, 1969), although the proximity of the two vessels is suggestive of such an arrangement (Fig. 2.5). The caudal branch on the left side of the carotid anastomosis, the left cervical artery, approached the attenuating vertebral, but both vessels diminished entirely before a union was formed. It appears from my series of vascular casts that the connection is never completed, and if it were formed by a very thin vessel that was lost in the cleaning process, such a small vessel surely could not be substantive enough to support the flow rates determined in the microsphere analysis. The inferior spinal artery, however, connects directly with the carotid vasculature near the base of the skull, leaving two avenues for the vertebral blood to reach the brain (Fig. 2.6). Blood from the inferior spinal artery could enter into the right carotid artery through the carotid anastomosis, and then enter the Circle of Willis in the dextral cerebral artery. Blood could also enter into the basilar artery and reach the brain as the basilar joins the Circle of Willis ventro-medially. (Neither the basilar artery nor the Circle of Willis in the rat snake is entirely homologous with the same-named structures in mammals; the mammalian basilar is defined as the union of the vertebral arteries, and the Circle of Willis as the union of the carotids and the vertebral-derived basilar.)

Once I established with microspheres that blood in the vertebral artery reaches the brain, and discovered with vascular casts a possible avenue, it was important to verify that blood in the spinal artery actually flowed anteriorly. Conventional wisdom, overlooking the connections of the vertebral artery, held that the spinal artery is fed by the carotid at the base of the head, and the presumed direction of flow is therefore posteriad (Fig. 2.8). Even Van Bourgondien and Bothner (1969), who identified connections between the vertebral and spinal arteries, maintained that the carotid anastomosis and the vertebral artery fed the inferior spinal artery from its anterior end. In the mammalian literature, posteriad flow in the spinal artery has been documented in a goat (Andersson and Jewell, 1956), but spinal flow is apparently craniad in several taxa (Hill, 1900; Gildea and Cobb, 1930; Baldwin and Bell, 1963c), at least when the other cephalic-contributing vessels are partially or completely ligated. Is it possible that the act of injecting suspended microspheres into the vertebral artery caused an increase in intraluminal pressure sufficient to reverse the direction of flow in the spinal artery, and that my observations are merely an inadvertent result of my treatment? I injected microspheres slowly at low pressures into the pulmonary venous return, so it seems very unlikely that introduction of microspheres into the rat snake circulation disturbed the cranial hemodynamics by means of pressure transients. It remains possible that artifacts

FIGURE 2.8. *Elaphe obsoleta*. Schematic diagram showing anterior blood vessels and presumed directions of flow. Conventional wisdom held that blood in the spinal artery flowed caudally, but in light of the newly realized connections with the anteriorly-flowing vertebral artery, and the results of the microsphere analysis, the direction of flow in the spinal artery must be scrutinized. Abbreviations as in Figures 1 and 5.


RCA
B
SA
?
CA
BA
LCA
VA

of flow directions were created by clamping either carotid or vertebral vessels (as in Baldwin and Bell, 1963b,c). However, introduction of microspheres directly into the vertebral artery with other vessels fully patent also demonstrated a vertebral contribution to cerebral perfusion. Furthermore, the results of radiographic imaging and direct observations of the inferior spinal artery confirm the craniad direction of blood flow from the vertebral artery to the brain.

The functional significance of the vertebro-spinal anastomoses is currently unclear. Perhaps the vertebral artery simply provides an alternate course of blood flow to the brain, serving as a safety factor in the event that flow in the single carotid is compromised. One intriguing variation on this theme is the possibility that the vertebral artery is an important source of cerebral blood during carotid impairment induced by gravity. That certain vessels are more susceptible to gravity is well documented. In humans and other primates, blood drains from the head through two routes, the intracavity (free-standing) jugular veins and the columnar (encased) vertebral venous plexus. In a horizontal posture, the jugulars are the sole route of cephalic drainage and the plexus is relatively inactive. However, when the animal adopts a head-up posture, the jugulars collapse and the plexus, with the structural support of the surrounding bone, becomes the primary avenue of venous flow from the head (this phenomenon is thoroughly discussed in chapters 3 and 4). Development of negative intraluminal pressure in the structurally-supported cranial veins that feed into the vertebral plexus is thought to facilitate cerebral perfusion.

Although arteries are considerably more rigid than are veins, they are still subject to collapse should arterial pressures fall to atmospheric levels. Cervical vessels in aquatic or non-climbing species of snakes may collapse to atmospheric (zero) pressures when these snakes are tilted head-up in air (Seymour and Lillywhite, 1976; Lillywhite and Pough, 1983; Lillywhite, 1993a; Young et al., 1997). Species with arboreal tendencies, such as *Elaphe obsoleta,* are generally protected from such postural failure of hemodynamics, except transiently at the onset of change from horizontal to vertical posture (Lillywhite and Seymour, 1978; Lillywhite, 1987). During head-up posture in *E. obsoleta*, cephalic blood flow is maintained by neurovascular reflexes, including posterior-to-anterior shunting of blood flow within the right aortic arch (Lillywhite, 1993b; Lillywhite and Donald, 1994). Constriction of the distal right aortic arch shunts blood craniad to both carotid and vertebral arteries, in which blood flows respond to gravitational stress, at least in viperids (Lillywhite, 1993a), in a parallel manner.

While it seems unlikely that vertebral-artery flow to the cerebral vasculature would assume prominence over carotid flow during gravitational stress induced by posture, the possibility is intriguing. Experiments by Henry et al. (1951) revealed that while flow in the carotid ceased in dogs exposed to hypergravity, cephalic supply continued through the protected vertebral and spinal vessels. Like the veins of the vertebral plexus, the vertebral artery enjoys structural support from the adjacent bones and surrounding musculature. It remains to be seen to what extent, if any, blood flow into the vertebral and spinal arteries of rat snakes and other tetrapods is favored by structural support and pressure gradients developed during head-up tilt, as has been postulated for the vertebral venous system of primates. Theoretically, the cerebral contribution of the vertebral artery in the inclined snake could become substantial.

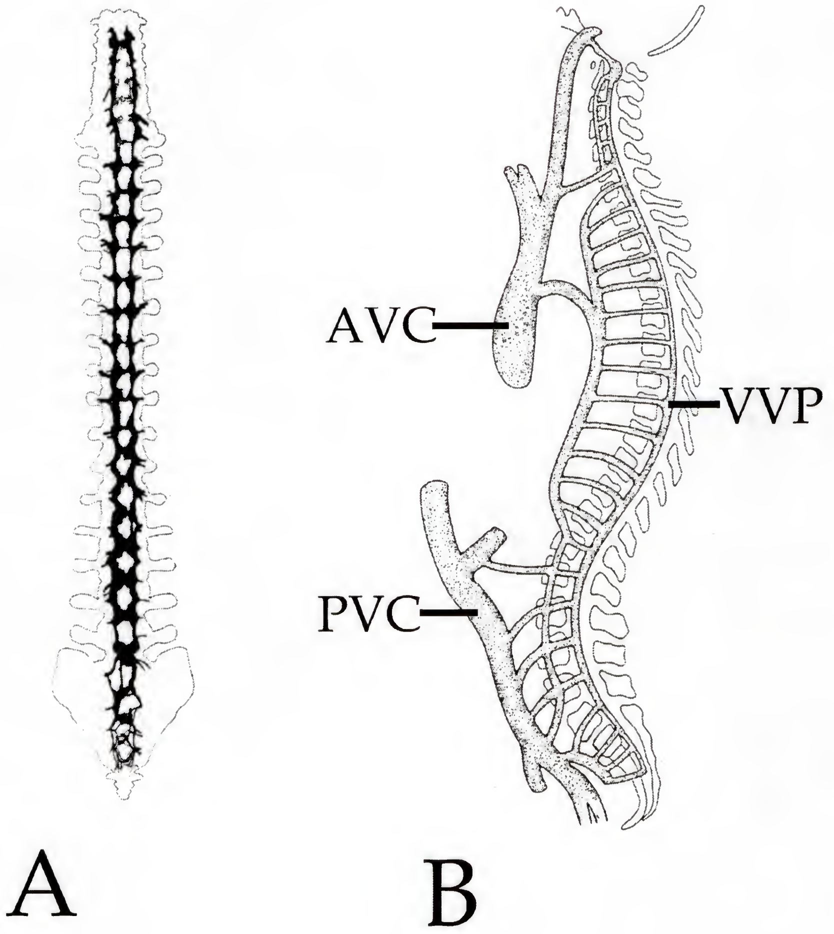
Repeating the microsphere analysis of flow distribution between carotid and vertebral arteries in snakes tilted to 90° would address this possibility.

CHAPTER 3
A NEW VASCULAR SYSTEM IN REPTILES: STRUCTURE AND FUNCTION OF THE VERTEBRAL VENOUS PLEXUS IN SNAKES.

Background

Plexiform spinal veins have been documented previously only in mammals (Batson, 1957; Barnett et al., 1958). The anatomy of this peculiar vascular arrangement, typically referred to as the vertebral venous plexus, has been thoroughly described in certain mammals (reviews in Worthman, 1956a; Batson, 1957; Barnett et al., 1958; Harris, 1964; Groen et al., 1997). In humans, the plexus originates anteriorly from the inferior petrosal and ventral occipital dural sinuses forming several valveless, longitudinal venous chains spanning the length of the vertebral column, extradurally, intra-osseously, and paravertebrally (Bowsher, 1954; Batson, 1957). The extradural system, or internal venous plexus, is the most extensive and voluminous component and is therefore the most easily demonstrable. It consists of two pairs of longitudinal vessels lying within the column, one smaller pair dorsal (posterior in the human anatomy literature) and one larger pair ventral (anterior) to the spinal cord. Segmental anastomoses between vessels of each pair create a ladder-like appearance in which the 'rungs' are formed beneath the vertebral arches by the anastomotic cross-branches, and the spaces occur where the intervertebral discs bulge into the spinal canal (Fig. 3.1A) (Batson, 1957). The dorsal portion of the internal plexus is less robust than the ventral and is more variable in form along the length of the column (Théron and Djindjian, 1973;

FIGURE 3.1. The vertebral venous plexus in a human (modified from Groen et al. 1997). **A.** Illustration of the anterior vertebral venous plexus. **B.** Schematic of the multiple connections of the vertebral venous plexus.


AVC
VVP
PVC
A
B

Groen et al., 1997). The basivertebral veins form a second system, coursing through the intra-osseous cavities of the vertebrae. The paravertebral system, or external venous plexus, forms a third network, running along the vertebral spines, around the column, and deeply penetrating the muscles of the dorsal parietes. Where they ascend through the transverse foramina of the cervical vertebrae, the vertebral arteries are also surrounded by a plexiform extension of this system (Harris, 1964; Dilenge et al., 1975).

Numerous transverse connections exist among these three longitudinal networks in mammals, especially in the cervical region (Eckenhoff, 1971). The plexus also has many anastomoses with caval and portal veins in the cranium, neck, thorax, abdomen, and (if present) the tail. Blood is thought to flow freely through the valveless plexus in multiple directions as a function of prevailing pressures (Batson, 1940, 1957; Herlihy, 1948; Tomlinson, 1956; Eckenhoff, 1970; but see Groen et al., 1997 re: functional valves). In essence, the vessels of the plexus connect while functionally bypassing the portal, pulmonary, and caval veins, and the vertebral veins are collectively recognized as the fourth venous system (Fig. 3.1B) (Batson, 1940; Worthman, 1956b).

Vascular casting conducted to demonstrate the arteries of the head and neck in the rat snake *Elaphe obsoleta* (chapter 2) indicated the presence of a vertebral plexus. As this system was previously known only in mammals, I here describe the anatomy and function of the plexus for the first time in a non-mammalian taxon.

Materials And Methods

Snakes of mixed sexes representing multiple taxa (Table 3.1) were shipped by air from a supplier in central Florida or donated by a local zoo. These animals represented

Table 3.1. Snake species, body measurements, and treatments used for venous plexus study.

Species	N	Mass (g)	SVL (cm)	Treatment
Colubridae				
Coluber constrictor	1	62	68	vascular cast
Elaphe obsoleta quadrivittata	3	230-503	90-118	fluoroscopy, vascular cast
E. o. quadrivittata	2	427, 481	105, 113	vascular cast
E. o. quadrivittata	1	525	121	histology
E. o. spiloides	1	432	103	fluoroscopy, vascular cast
Nerodia fasciata fasciata	1	112	52	vascular cast
Opheodrys aestivus	1	27	52	vascular cast
Boidae				
Boa constrictor	1	1811	144	vascular cast
Python molurus bivittatus	2	152, 213	52, 58	fluoroscopy, vascular cast
P. m. bivittatus	2	115, 201	48, 57	vascular cast
Python regius	1	232	57	vascular cast
Viperidae				
Crotalus adamanteus	1	255	61	vascular cast

uncosmetic (scarred, blemished, scratched, or otherwise imperfect) specimens from the pet trade and salvaged eggs from an undesired breeding at the zoo. To study the anatomy of the circulatory system, I injected methyl methacrylate into the vessels of fresh cadavers and digested the flesh and bones in corrosive baths to isolate resinous casts of the circulatory system (as in chapter 2). A portion of the vertebral column was removed from one cadaver and used to prepare histologic sections. Tissues were fixed in neutral buffered formalin, decalcified in 5% acetic acid, and embedded in paraffin. Six-micron sections were then generated and stained using routine Harris hematoxylin and eosin procedure.

I also used fluoroscopy to visualize postural effects on patterns of venous return from the head in six animals (see methods in chapter 2 for details of surgical and radiographic techniques). Polyethylene catheters were surgically introduced into selected blood vessels and secured non-occlusively. After a minimum 24 hr recovery period, contrast medium was introduced through a carotid artery catheter (N=5), as the carotid is the primary artery supplying blood to the head (chapter 2, this study), or through a pulmonary vein catheter (N=1) so that any pressure artifacts induced by contrast injection could be dissipated during passage through the heart. Patterns of blood flow were then observed using a C-arm fluoroscope. Snakes were restrained in transparent acrylic tubes slightly larger than their girth, and posture was changed repeatedly (three times per animal) by tilting the tubes from horizontal to vertical head-up positions. In one animal, I also imaged venous return during vertical head-down tilting. The Institutional Animal Care and Use Committee of the University of Florida approved all research on these animals.

Results

Vascular Casts

The anatomy of the vertebral veins in all snakes examined is similar enough to allow a general description. Blood from the brain can drain ventrally through the oblique palatine vein, laterally through the median cerebral veins, or dorsally through the longitudinal cerebral vein (see Bruner, 1907 or O'Donoghue, 1912 for a detailed description of cranial vascular anatomy). The two median cerebrals pass into the longitudinal vein above the medulla, and the longitudinal then bifurcates giving rise to two posterior cerebral veins (Fig. 3.2A). These vessels exit the cranium at the lateral edges of the foramen magnum. Between the occipital bones and the atlas, the posterior cerebrals communicate dorsally with each other via an arch over the spinal cord, and laterally with small communicating vessels to the right and left lateral cephalic veins (branches of the jugular veins). Caudal extensions of the posterior cerebral veins enter the vertebral column forming two lateral vessels within the atlas that unite ventrally within the axis by way of some peculiar vascular rings (Fig. 3.2B) to form the internal vertebral plexus. The longitudinal vessels of the internal plexus extend caudally within the vertebral column to the tip of the tail, bifurcating at each intervertebral joint and re-uniting intravertebrally, creating the typical ladder-like formation (Fig. 3.2B,C; compare to Fig. 3.1B).

Only the single, ventral pair of longitudinal vessels was demonstrated in the internal plexus; however, a dorsal arch connects these vessels above the spinal cord at each vertebral joint (Figs. 3.2A,D,F,3.3C). Beginning at the atlas-axis junction, a single,

FIGURE 3.2. Corrosion casts of the cervico-cephalic vasculature; anterior to the left. **A.** *Elaphe obsoleta:* cranial origin of the vertebral venous plexus from the posterior cerebral veins at the base of the skull; dorsal view. **B.** *Elaphe obsoleta:* cranial origin of the plexus with demonstration of the vascular rings at the atlanto-axis joint; ventral view. **C.** *Elaphe obsoleta:* isolated vessels of the internal plexus showing symmetry and lozenge or ladder-like structure of the internal plexus; dorsal view. **D.** *Elaphe obsoleta:* a supraspinous vein connects the dorsal arches of the internal plexus; lateral view. **E.** *Elaphe obsoleta:* posterior to the first several cervical segments, the supraspinous vein arises from segmental interspinous veins. A zygopophyseal sinus lies medio-caudal to the articulation of the bony zygapophyses; lateral view. **F.** *Python molurus:* a fine mesh of veins surrounds the spinal cord; lateral view. DA, dorsal arch of the internal plexus; ISV, interspinous veins; LV, longitudinal vein; LCV, lateral cephalic veins; MCV, median cerebral veins; PCV, posterior cerebral veins; SA, spinal artery; SSV, supraspinous vein; VR, vascular rings; VVP, vertebral venous plexus; ZA, zygopophyseal articulation; ZS, zygopophyseal sinus.

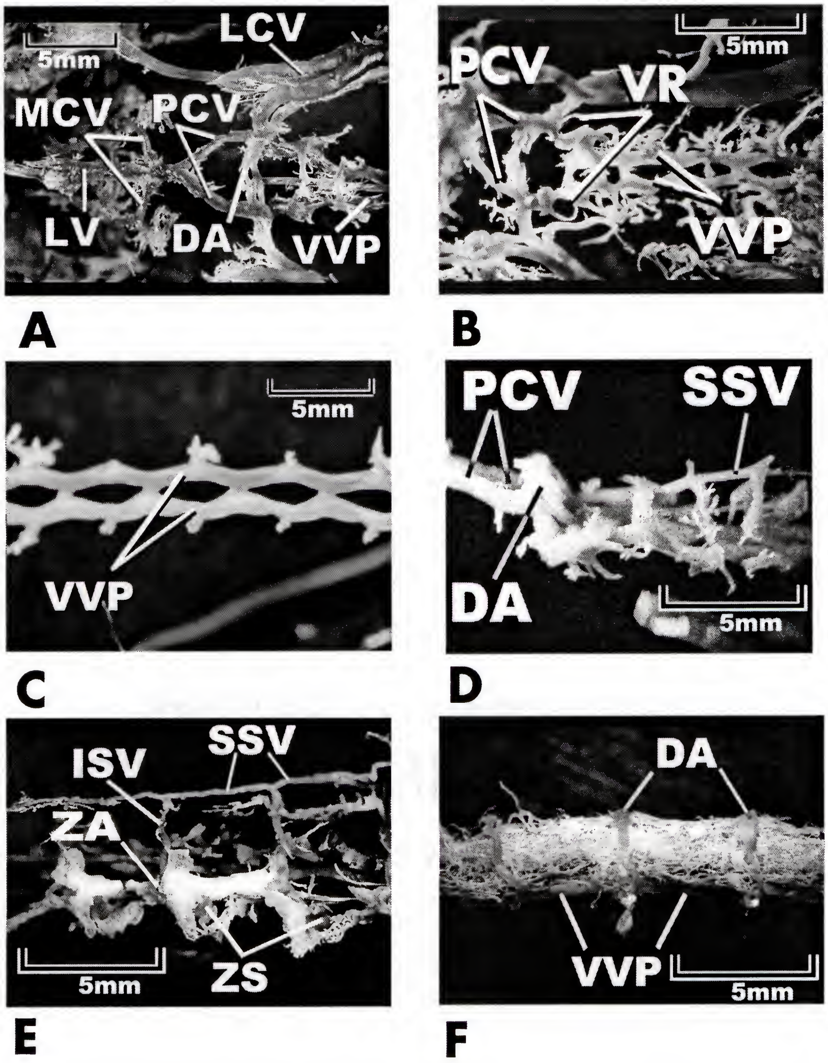
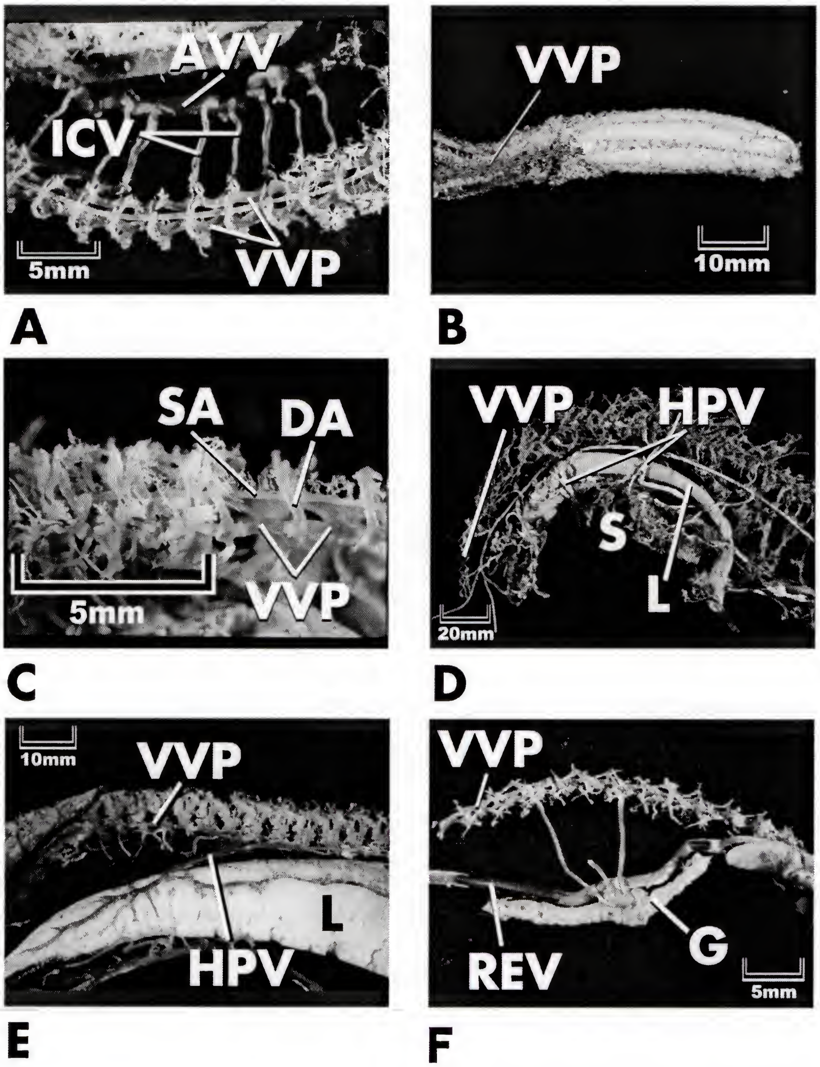

5mm
LCV
MCV
PCV
LV
DA
VVP
A
5mm
PCV
VR
VVP
B
5mm
VVP
C
PCV
SSV
DA
5mm
D
ISV
SSV
ZA
5mm
ZS
E
DA
VVP
5mm
F

FIGURE 3.3. Corrosion casts; anterior to the left. **A.** *Elaphe obsoleta:* numerous anastomoses connect the anterior vertebral vein and the venous plexus via the intercostal veins; dorsal view. **B.** *Crotalus adamanteus:* the caudal plexus lying on the dense capillaries of the shaker muscle; dorsal view. **C.** *Python molurus:* the external plexus and lymphatic vessels have been removed posteriorly to reveal the internal plexus; lateral view. **D.** *Crotalus adamanteus:* robust hepatico-parietal veins connect the portal and spinal veins; ventral view. **E.** *Python molurus:* numerous hepatico-parietals form longitudinal vessels that anastomose extensively with the plexus; lateral view. **F.** *Opheodrys aestivus:* the renal efferent veins, where they lie adjacent to the gonads, typically have robust connections with the plexus; ventral view. AVV, anterior vertebral vein; DA, dorsal arch of internal plexus; G, gonad; HPV, hepatico-parietal vein; ICV, intercostal vein; L, liver, REV, renal efferent vein; S, vasculature of the stomach, which sits in the crescent of the liver; SA, spinal artery; VVP, vertebral venous plexus.


AVV
ICV
VVP
5mm
A
VVP
10mm
B
SA
DA
VVP
5mm
C
VVP
HPV
S
L
20mm
D
10mm
VVP
L
HPV
E
VVP
REV
G
5mm
F

median, longitudinal vessel (the supraspinous vein) connects these arches dorsally (Fig. 3.2D). It arises directly from the peak of the arches in the first several cervical segments, but from vertical interspinous veins thereafter, forming a longitudinal, subcutaneous, supraspinous vein (Fig. 3.2E). A small sinus arises from the internal plexus caudal to each venous arch; it lies medio-caudal to the articulation of the zygapophyses (Fig. 3.2E). This zygopophyseal sinus gives rise to a thin vessel that passes dorsolaterally between the vertebrae into the musculature. A fine network of vessels was demonstrated around the spinal cord in several species, but it is unclear if these invest the dura or the surface of the cord itself (Fig. 3.2F).

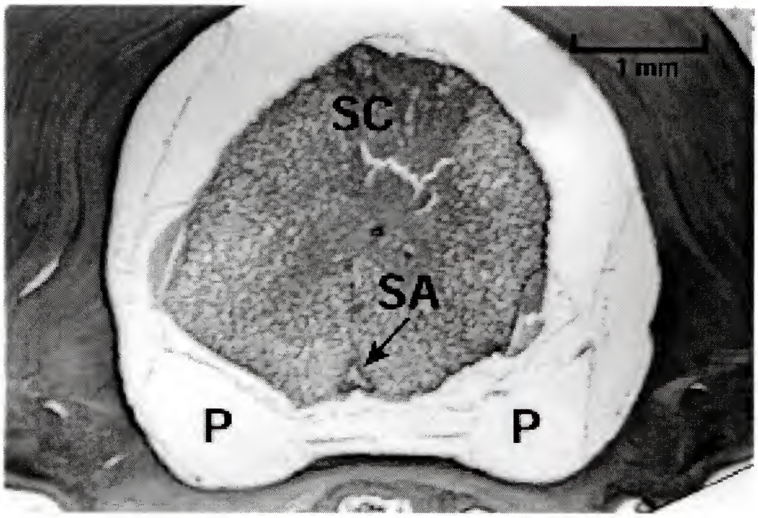
There is apparently no intra-osseous component to the vertebral plexus of snakes. Occasionally, small vessels do pass ventrally through the vertebral bodies, but no basivertebral veins were found to course longitudinally within the bone of the vertebral column. An external plexus was present, insofar as numerous diminutive vessels course around the column connecting the internal plexus with the dorsal musculature and caval veins. At each convexity of the internal plexus, where it gives rise to the dorsal arch and the zygopophyseal sinus, a lateral intervertebral vein passes out between the vertebrae. The intervertebral receives a small parietal vein from the dorsal musculature, a caudal branch from the paravertebral lymphatic vessels, and continues ventrolaterally as an intercostal vein (Fig. 3.3A). Other vessels permeate the musculature and surround the column; they are remarkably dense in the epaxial musculature of *Coluber constrictor* and in the shaker muscle of *Crotalus adamanteus* (Fig. 3.3B). Many of the terminal vessels external to the vertebral column of snakes are small in caliber, and some might be components of, or connectives with, the lymphatic system (Fig. 3.3C).

Multiple anastomoses between the internal plexus and the caval veins exist along the length of the vertebral column. Anterior to the heart, the jugulars communicate with the plexus only at the foramen magnum (Fig. 3.2A), while the anterior vertebral vein shares numerous transverse connections with the plexus via the intercostal veins (Fig. 3.3A). Proceeding caudally, the plexus communicates with the anterior vena cava at the level of the heart, the posterior vertebral vein, the posterior vena cava, the hepatic portal vein, the renal efferent and renal portal veins, and the caudal vein, but with none as extensively as with the anterior vertebral vein. However, connections between the plexus and hepatic portal vein, i.e., the hepatico-parietals, are noteworthy in *Crotalus adamanteus* and *Python molurus*, at the level where the portal vein courses into the liver. Where the stomach overlies the liver, the hepatico-parietals are remarkably large in *C. adamanteus* (Fig. 3.3D). In *P. molurus*, the hepatico-parietals are abundant and frequently form longitudinal vessels within the dorsal musculature above the liver; these vessels anastomose extensively with the vertebral plexus (Fig. 3.3E). Robust connections between the caval veins, specifically the renal efferent veins, and the plexus are also usually prominent in the vicinity of the gonads (Fig. 3.3F).

Histology

Transverse sections through the vertebral column of the rat snake revealed the relation between the internal vertebral plexus and the soft and bony tissues of the spine. The two large channels of the internal plexus lie beneath the spinal cord and spinal artery within the neural canal (Fig. 3.4). In some sections, erythrocytes were clearly distinguishable, at higher power, within the vessels of the internal plexus.

FIGURE 3.4. *Elaphe obsoleta.* Histologic section through the vertebral column; dorsal up. SA, spinal artery; SC, spinal cord; P, venous channels of the internal plexus.


1 mm
SC
SA
P
P

Fluoroscopy

Fluoroscopy in conscious snakes allowed direct visualization of fluid movement from the carotid vasculature of the head into the two venous systems. In the horizontal posture (Fig. 3.5A), blood drained from the head primarily through the jugular veins, while the plexus was only occasionally faintly indicated. In snakes tilted vertically head-up (Fig. 3.5B), the plexus became the principal route of cephalic venous drainage and the jugulars were only faintly indicated, if at all. In the relatively smaller pythons, the high pressure associated with injecting viscous contrast medium into small vessels was observed on several occasions to cause considerable jugular return in the vertical posture, and in one instance, retrograde flow in the vertebral artery. However, in the small rat snake cannulated in the pulmonary vein, contrast medium passed through the heart and up the carotid, and no jugular return was evident. During vertical head-down tilt, the jugular veins became greatly engorged and no venous return was evident in the vertebral column.

Discussion

Longitudinal (non-plexiform) veins within the vertebral column, i.e., simple spinal veins, have been noted in the snake *Tropidonotus natrix* (= *Natrix natrix*) (Bruner, 1907; O'Donoghue, 1912). These paired vessels were described originating at the base of the head and entering the vertebral column, where they united beneath the spinal cord as a single, diminutive vessel that coursed caudally. However, these investigators failed to realize the magnitude and significance of the entire vertebral venous system. I have revealed that ophidian spinal veins form an elaborate vertebral plexus extending from the base of the skull to the tip of the tail (Fig. 3.6). This system has robust connections with the other venous systems and appears to play a critical role in postural hemodynamics.

Anatomic Considerations

The anatomy of the plexus in snakes is similar to that in mammals, with several notable exceptions. I did not detect a dorsal portion of the internal plexus, as has been done in several human studies (Groen et al., 1997; but see Hirabayashi et al., 1996). Worthman (1956a,b) did not detect any dorsal vessels in dogs, but rather observed direct dorsal connections between the ventral vessels, as I did in snakes. Geiger and Magnes (1947) found that the same arrangement obtains in the cat. Herlihy (1948) observed dorsal vessels in cats, but only in the upper portion of the cervical region, where in snakes I observed a single median vessel. The dorsal portion of the spinal vein is certainly well developed in pinnipeds and archosaurs. In seals, the dorsal vein is robust and the ventral portion is absent or present only as occasional ventral branches connecting the dorsal vessels (Harrison and Tomlinson, 1956). A similar arrangement is found in birds (Baumel, 1975, 1988 ; chapter 5 of this study) and crocodilians (Rathke, 1866; chapter 5 of this study).

An external vertebral plexus was present in all snakes examined and is intimately associated with the paravertebral lymphatic system via myriad connectives. Numerous anastomoses connect the caval veins and the plexus; these are the intercostal and intervertebral veins of other authors (e.g., Beddard, 1904a,b, 1906a; O'Donoghue, 1912). I did not detect an intra-osseous component of the vertebral plexus in any snake species.

FIGURE 3.5. *Elaphe obsoleta.* Fluoroscopic images showing postural effects on venous return from the head. **A**: In the horizontal posture, venous return occurs exclusively through the jugular veins. **B**: During head-up tilt, venous return is transferred to the vertebral venous plexus. QM, quadrato-mandibular articulation (for reference); JV, jugular vein; VVP, vertebral venous plexus.

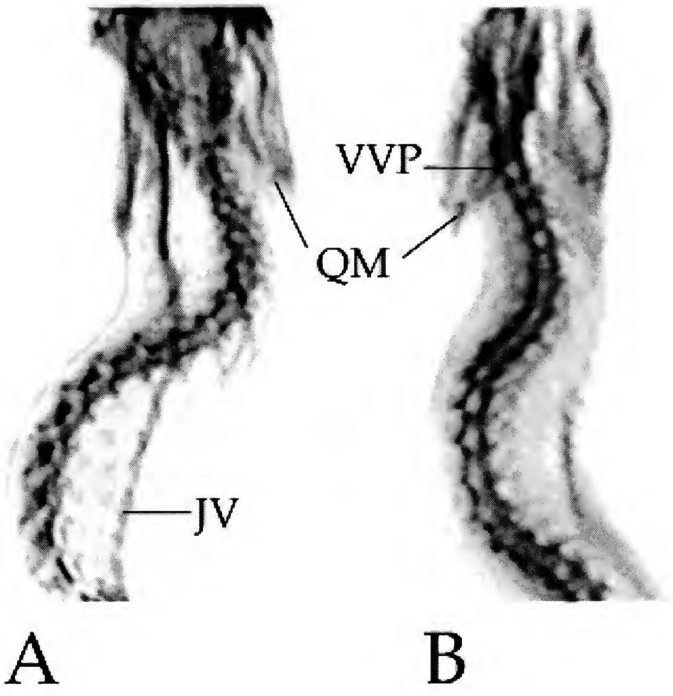
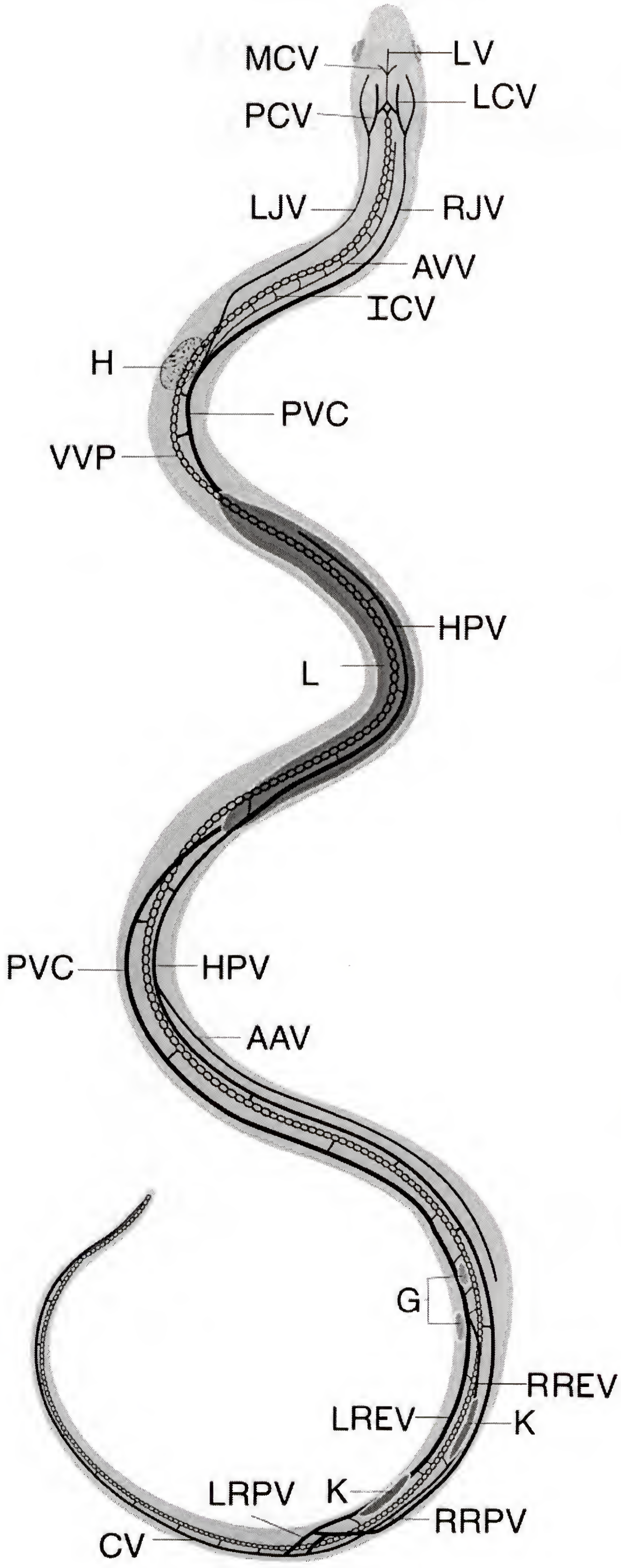

VVP
QM
JV
A
B

FIGURE 3.6. Composite illustration of the vertebral venous plexus and its connections with the caval veins. AAV, anterior abdominal vein; AVV, anterior vertebral vein; CV, caudal vein; G, gonad; H, heart; HPV, hepatic portal vein; ICV, intercostal vein; K, kidney; L, liver; LV, longitudinal vein; LCV, lateral cephalic vein; LJV, left jugular vein; LREV, left renal efferent vein; LRPV, left renal portal vein; MCV, median cerebral vein; PCV, posterior cerebral vein; PVC, posterior vena cava; RJV, right jugular vein; RREV, right renal efferent vein; RRPV, right renal portal vein; VVP, vertebral venous plexus.


MCV
LV
PCV
LCV
LJV
RJV
AVV
ICV
H
PVC
VVP
HPV
L
PVC
HPV
AAV
G
RREV
LREV
K
K
LRPV
RRPV
CV

My findings are in opposition to those of previous works on the anatomy of the reptilian lymphatic system. One major treatise on reptilian anatomy (Ottaviani and Tazzi, 1977) portrayed lymph vessels within the vertebral column in an arrangement similar to what I observed with the venous plexus. Lymphatic vessels often accompany blood vessels, usually perivascularly in snakes (Chapman and Conklin, 1935). However, it seems unlikely that the authors would describe the lymphatic system in such detail without acknowledging an accompanying plexus of veins that was at that point unknown in reptiles. A more likely explanation is that the vertebral plexus was erroneously identified as a component of the lymphatic system. Other studies of snakes, humans, and tetrapods in general do not describe lymphatic vessels within the vertebral column, and the central nervous system is classically referred to as the only tissue without lymph drainage (Chapman and Conklin, 1935; Kampmeier, 1969; Gray, 1995). However, spinal veins of some form have been described in representatives of most major vertebrate lineages and seemingly represent a synapomorphy for the group (Table 3.2). In chondrichthyans, these vessels might be longitudinal (O'Donoghue, 1914), rhomboidal (Parker, 1886), or in the form of voluminous sinuses (Kampmeier, 1969). Some spinal vessels in teleosts have been described as lymphatic (Kampmeier, 1969), but spinal veins with distinct connections to the cardinal system have been identified in other osteichthyans (Owen, 1866). Some amphibians possess a simple longitudinal spinal vein dorsal to the cord (Francis, 1934; Millard, 1941), but the serpentiform salamander *Amphiuma means* has a ventral plexiform system similar to that of snakes (KCZ, pers.

Table 3.2. Vertebrate taxa in which spinal veins have been demonstrated and described.

Taxon	Form	Source
Chondrichthyes		
dogfish	simple dorsal and	O'Donoghue, 1914
shark	ventral	Parker, 1886
ratfish	dorsal rhomboidal	Kampmeier, 1969
	dorsal sinuses	
Osteichthyes		
unspecified	simple ventral	Owen, 1866
Amphibia		
fire salamander	simple dorsal	Francis, 1934
clawed frog	simple dorsal	Millard, 1941
amphiuma	ventral plexus	KCZ, pers. obs.
Chelonia		
pond turtle	simple ventral	Bruner, 1907
Florida softshell	dorsal sinus	KCZ, pers. obs.
"Lacertilia"		
wall lizard	simple ventral	Bruner, 1907
common iguana	gracile ventral plexus	KCZ, pers. obs.
Egyptian mastiguire	gracile ventral plexus	KCZ, pers. obs.
savanna monitor	robust ventral plexus	KCZ, pers. obs.
Serpentes		
grass snake	simple ventral	O'Donoghue, 1912
many others	ventral plexus	this study; see Table 3.1
Crocodylia		
all crocodilians	dorsal sinus	Rathke, 1866; chap. 5 this study
Aves		
pigeon	dorsal sinus	Baumel, 1988
chicken	dorsal sinus	Baumel, 1975
ratites	dorsal sinus	chap. 5 this study
Artiodactyla		
goat, sheep	ventral plexus	Herlihy, 1948
pig	ventral plexus	Nystrom et al., 1998
"Ruminantia"	unspecified	Breschet, 1828-32 (*fide* Batson, 1957)
"Bimana"		
unspecified	? plexus	Owen, 1868

Table 3.2. continued

Taxon	Form	Source
Carnivora		
cat	ventral plexus	Herlihy, 1948
dog	ventral plexus	Worthman, 1956a
otter	paired dorsi-lateral	Harrison and Tomlinson, 1956
"Carnivora, Plantigrada"	unspecified	Breschet, 1828-32 (*fide* Batson, 1957)
unspecified	? plexus	Owen, 1868
Cetacea		
all cetaceans	paired ventral sinuses, more dextral in some, plexiform in neck	Fawcett, 1942; Slijper, 1962; Harrison and Tomlinson, 1956
Chiroptera		
unspecified	unspecified	Slijper, 1962
Edentata		
sloths	dextral sinus, ventral plexus anteriorly	Barnett et al. 1958
Lagomorpha		
rabbit	? plexus	Batson 1944
"Pachydermata"		
unspecified	unspecified	Breschet, 1828-32 (*fide* Batson, 1957)
Pinnipedia		Barnett et al., 1958, Ronald et al., 1977
seals, sea lion	dorsal sinus, ventral pair in neck	
Perrissodactyla		
"Solidungula"	unspecified	Breschet, 1828-32 (*fide* Batson, 1957)
Primates		
human	ventral plexus	Groen et al., 1996
orangutan, langur	unspecified	Van Gelderen, 1924,1925 (*fide* Barnett et al., 1958)
rhesus monkey	ventral plexus	Batson, 1940
baboon, vervet, bushbaby	ventral plexus	Lake et al., 1990
all lorisids	ventral plexus	Hill, 1946; Davies, 1947; Barnett et al., 1958
"Quadrumana"		
unspecified	? plexus	Owen, 1868

Table 3.2. continued

Taxon	Form	Source
Rodentia		
rat	unspecified	Bowsher, 1954
beaver	unspecified	Franklin, 1937 (*fide* Worthman, 1956a)
unspecified	unspecified	Breschet, 1828-32 (*fide* Batson, 1957)
Sirenia		
manatee	ventral plexus, with dorsal portion in neck	Fawcett, 1942; Barnett et al., 1958

obs.). Bruner (1907) observed simple spinal veins in the lizard *Lacerta agilis* and in the turtle *Emys europæ (= E. orbicularis?).* A rudimentary plexus is demonstrable in iguanian lizards, but varanids possess an extensive plexus comparable to that of snakes, with the addition of major pelvic and pectoral branches (KCZ, pers. obs.). Columbiform, galliform (Baumel, 1975, 1988), and ratite birds (chapter 5 this study), as well as crocodilians (Rathke, 1866; chapter 5 this study), have voluminous spinal veins that originate from an enlarged occipital sinus and extend caudally dorsal to the cord. In mammals, spinal veins are found in the form of a ventral plexus, ventral sinus, dorsal sinus, simple paired dorso-lateral vessels, and a dextral sinus (see Table 3.2 for references). Clearly, spinal veins are taxonomically widespread, while spinal lymphatics have only been tenuously identified in one group of advanced fishes (teleosts). My studies of comparative anatomy, histology, and hemodynamics leave no doubt that the vessels I describe in snakes are indeed veins.

Functional Considerations

Although the anatomy of the vertebral venous plexus has been well documented in a number of mammalian taxa, its function has not been so rigorously explored. The plexus has been observed to act as a collateral route of venous return to the heart after occlusion or ligation of various veins in the caval system (Batson, 1944, 1957; Worthman, 1956b and therein; Barnett et al., 1958 and therein). In pinnipeds and sloths, the spinal veins are normally the only avenue for venous return from some parts of the body (Wislocki, 1928; Harrison and Tomlinson, 1956). The plexus also acts as a vascular bypass during transient increases in thoraco-abdominal pressure induced by coughing and defecation (Batson, 1957), micturition (Herlihy, 1948), lifting and the

Valsalva maneuver (Batson, 1957; Eckenhoff, 1970), abdominal tumors (Pritchard et al., 1955; Scott, 1963), position of the viscera (Herlihy, 1948), activity of the abdominal muscles (Youmans et al., 1963), normal respiration (Reitan, 1941; Herlihy, 1948; Brecher, 1956; Eckenhoff, 1970), and the manual application of external pressure (Batson, 1940, 1957; Herlihy, 1948; Epstein et al., 1970; but see Worthman, 1956b). Under these various conditions, caval venous pressures rise sharply (e.g., Brigden et al., 1950; Scott, 1963) and blood is forced out of the thoraco-abdominal veins and shunted into the plexus. Because of its vast connections throughout the body and lack of valves, the plexus has also been implicated in the multi-directional transfer of disease and air emboli between distant organs and systems (Batson, 1940, 1957; Eckenhoff, 1970). Radiographic and flowmetric studies have indeed verified different directions of flow through the spinal veins under various conditions in primates (Batson, 1940, 1957; Epstein et al., 1970; Dilenge and Perey, 1973; Dilenge et al., 1975), dogs (Herlihy, 1948; Tomlinson, 1956; Worthman, 1956b), cats, sheep, goats (Herlihy, 1948), and seals (Harrison and Tomlinson, 1956; Ronald et al., 1977; Nordgarden et al., 1998).

Blood flow through the vertebral plexus is also affected by gravitational stress induced by posture. In humans and other primates, the plexus is a gravity-sensitive network and has been demonstrated radiographically to be the principal route of cerebral venous drainage in upright subjects (Epstein et al., 1970; Dilenge and Perey, 1973; Dilenge et al., 1975; Kornienko and Shubin, 1978). Although it is primarily the jugular veins that drain the head in horizontal subjects, direct observations reveal that gravity causes the jugulars to collapse, at least partially, in upright humans (Brecher, 1956; Knebel and Ockenga, 1960; Duomarco and Rimini, 1962; Gauer and Thron, 1965;

Eckenhoff, 1966; Blomqvist and Stone, 1983; Pedley, 1987; Ganong, 1995), giraffes (Goetz and Keen, 1957; Pedley, 1987), and dogs (Franklin, 1937; Holt, 1941; Brecher, 1956; Alexander, 1963). The radiographic studies (cited above) support these observations: little jugular activity is observed during upright posture. Venous return in upright primates occurs primarily through the encased plexus, which remains patent due to the structural support of the surrounding bone (Epstein et al., 1970; Dilenge and Perey, 1973). Considering that humans spend most of their time in vertical sitting or standing postures, the vertebral plexus must be considered the primary avenue of venous return from the head (Dilenge and Perey, 1973).

Rat snakes and juvenile Burmese pythons are semi-arboreal and frequently adopt a vertical posture while climbing trees, thereby subjecting the blood in their vessels to gravitational stress. As has been observed in many mammals, jugular collapse appears to be evident in some species of vertically tilted snakes (Seymour and Lillywhite, 1976; Lillywhite and Pough, 1983; Lillywhite, 1993a). I have demonstrated that, as in primates, jugular collapse in upright snakes is associated with passage of venous blood into the vertebral plexus. Bruner (1907), based on his anatomical observations, estimated that the internal jugular vein in reptiles would carry 90% of the blood from the head, the rest passing through the external jugulars, spinal veins, and other "small" vessels. At least in snakes, this supposition is incorrect for animals in vertical postures.

Passage of cerebral efflux into the plexus of upright animals is not of trivial importance; in fact, it might significantly influence the supply of blood to the brain. The plexus conceivably facilitates cerebral perfusion during vascular stress caused by upright posture. Gravity pulls on the blood in vertical vessels inducing gravitational pressure gradients that are lower at the top. Arterial pressure is relatively high in the horizontal position, and although it can fall with upright posture, it must remain at least 20 mm Hg above atmospheric in humans or consciousness is lost (Henry et al., 1951). Blood pressure in the superior veins drops in parallel. The jugular veins begin at relatively lower intraluminal pressures, and as their intraluminal pressures approach zero, these compliant vessels tend to collapse (references above). The vertebral venous plexus, on the other hand, is maintained open by periosteal adhesion to the surrounding bone. Blood pressure leading into the vertebral veins continues to drop to sub-atmospheric levels (e.g., Guyton and Hall, 1996) and their rigidity prevents collapse. The vertebral plexus thus provides a patent route of lower pressure for venous return from the head. Provision of a low-pressure pathway for cerebral effluence in the face of reduced arterial pressures maintains a favorable perfusion gradient across the brain during upright posture. This idea is explored further in Chapter 4.

The system functions in reverse during head-down posture in primates, with blood from the posterior extremities being shunted into the plexus and then into the superior vena cava prior to being returned to the heart (Dilenge and Perey, 1973). The distended dural sac occludes the plexus at the lower end, so that usually, only one end of the plexus is thought to be functional at any given time. My observations of snakes tilted head-up and head-down support this view.

Although some critics have questioned the ability of the plexus to function as a collateral route of venous flow (see comments of Dean in Falk, 1990), the fact that radiologic studies have verified this repeatedly (see above) and that the plexus can immediately accommodate the venous return after bilateral jugular ligation or ligation of the azygous vein and the anterior vena cava (Batson, 1944; Worthman, 1956b; Barnett et al., 1958 and therein) is irrefutable.

Future Directions

The vertebral plexus also facilitates venous return from the posterior extremities in supine pregnant women, where the gravid uterus temporarily occludes the posterior vena cava. With the vena cava physically blocked by the gravida, blood is shunted into the plexus to circumvent the obstruction (Hirabayashi et al., 1996). However, there is often still a drop in systemic blood pressure (Brigden et al., 1950) and a marked decrease in cardiac output (Vorys et al., 1961) compared to the supine post-partum subject. These effects can be significant enough to cause unconsciousness (supine shock syndrome; Brigden et al., 1950).

Snakes provide an analogous if somewhat extreme example of the effect of a foreign body in the abdominal cavity. Almost all snakes swallow prey whole; most snake species (90% or more) eat prey that are large relative to their body size (Rage, 1994). Some snake species are specialized durophages, feeding on large and hard items such as calcareous eggs, hard-bodied lizards, and arthropods (Savitzky, 1983). Such feats might not be possible without collateral routes of blood flow. Preliminary observations using MRI indicate that when a snake eats a large prey item, the distended stomach acts analogously to the gravid uterus in humans by disrupting the continuous flow of blood (KCZ, unpubl. data). The vertebral plexus conceivably allows shunting around the obstruction and thus continuous venous return from the posterior tissues during the extended process of ingestion and digestion. The hepatico-parietal veins that connect the plexus to the hepatic portal vein over the liver and stomach are well developed in the species that are known to feed on large prey, e.g., those of the genera *Crotalus*, *Python*, *Heloderma,* and *Varanus* (see also Beddard, 1906a). Clearly, species of *Crotalus* and *Python* exhibit a suite of physiological adaptations of the gut for ingesting large prey (Secor et al., 1994; Secor and Diamond, 1995).

I suspect that any large foreign body in the snake abdomen, be it ingesta, eggs, or embryos, would affect hemodynamics adversely. Pregnant snakes often stop feeding for the duration of the gestation period. Perhaps feeding and pregnancy are mutually exclusive activities because of spatial limitations within the abdominal cavity. The presence of a distended gut could potentially disrupt circulation in the mother or the embryos. Snakes are especially sedentary during digestion and gestation. Perhaps caval occlusion causes a drop in systemic blood pressure, analogous to supine shock syndrome in pregnant humans. Note also that some of the arteries supplying blood to the head, vessels that conceivably could become occluded during swallowing, might be protected by structural support from the vertebral column (e.g., Figs. 2.3,2.4). Investigation of these questions awaits development of more sophisticated monitoring equipment that will allow observation of blood flow during these dynamic activities.

CHAPTER 4
SUPERIOR BLOOD CIRCUITS REVISITED: THE ROLE OF SPINAL VEINS IN THE SIPHON CONTROVERSY.

Background

There has been considerable debate in the literature regarding venous return and energy expenditure in vertical blood circuits. One group claims that a siphon-like mechanism is in effect whereby the descent of blood in the jugular veins facilitates the ascent of blood in the carotid arteries (e.g., Badeer and Hicks, 1997 and therein). Gravitational considerations are thus alleviated, and the heart expends only as much energy as it would if that system were horizontal, i.e., just that amount required to overcome resistance from viscosity and angioarchitecture. Another faction notes that jugular veins are collapsible and reasons that a siphon-like effect is only possible in a system of rigid conduits where the liquid is continuous and gravitational pressure gradients in ascending and descending limbs are equivalent (e.g., Pedley et al., 1996 and therein). They liken venous return through collapsible jugulars to a vascular waterfall where gravitational energy is not reclaimed but rather is lost as frictional heat to the walls of the collapsed vessels. Both groups have relied extensively on laboratory models and mathematical manipulations of the physical equations of Bernoulli and Poiseuille.

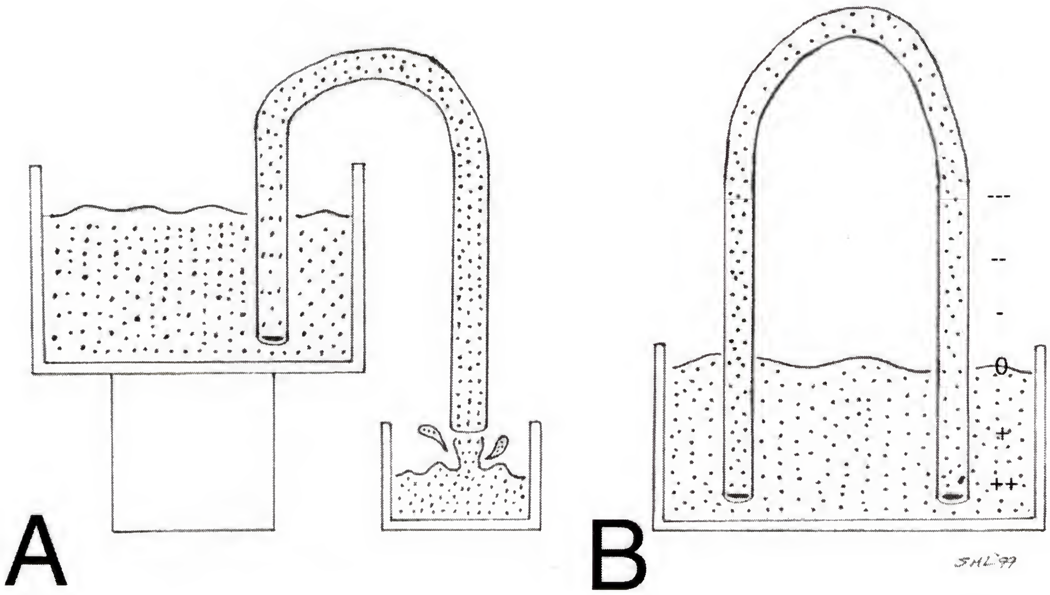
In the previous chapter, I demonstrated that snakes possess a robust system of spinal veins that play an important role in postural hemodynamics. I also reviewed an extensive and apparently overlooked literature describing this system in mammals. In light of this information, I wish to help clarify the siphon controversy by drawing focus away from the role of the jugular veins in vertical circuits.

A Siphon Defined

A siphon is simply a liquid-filled tube used to drain a reservoir. The high end of the siphon tube is immersed in the reservoir and the low end is either open to the atmosphere at any point lower than the liquid surface, or it is immersed in a second reservoir in which the liquid surface is lower than that of the first reservoir (Fig. 4.1A). The liquid moves from a point of higher gravitational potential energy in the upper reservoir to one of lower gravitational potential energy near the ground. The distinction between a siphon and a drain is that some portion of the siphon tube passes above the liquid surface in the upper reservoir; the liquid first moves up (against gravity) before it moves down. The liquid goes through a 'transitional state' at the summit where its gravitational potential energy is higher than it was in the upper reservoir, but this is possible because the final gravitational potential energy near the floor is much lower. The only energy required to begin the process is to bring the liquid over the summit and to the point where the liquid level in the descending tube is just below that in the higher reservoir. From that point on, liquid draining down the longer descending arm of the siphon draws liquid up the shorter ascending arm, and siphoning continues without the input of additional energy.

Physiologists studying the cardiovascular system have taken a keen interest in the "inverted U" portion of the siphon, which superficially resembles the circulation above the heart in an upright tetrapod (Fig. 4.1B). The idea that liquid descent in one arm of a

FIGURE 4.1. The siphon principle. **A.** Water is siphoned from a tank to a bucket, moving to a state of lower gravitational potential energy. Note that the water first moves up (relative to the water surface) before it goes down. **B.** An isolated portion of a siphon, the inverted U tube. Gravity pulls on the liquid and creates a vertical pressure gradient. At the level of the water surface, gravitational pressure is atmospheric or zero. Gravitational pressure is increasingly negative moving up both 'arms' of the loop from the water surface, and increasingly positive below.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vertical circuit could influence liquid ascent in the other is appealing in terms of optimization and energy conservation. The common model of the superior circulation has the inverted U portion of the siphon with both arms of equal length and immersed a common reservoir (e.g., Fig. 4.2,4.3). Liquid is re-circulated and does not achieve a lower energetic state, so some energy is required to perfuse the loop, but no more than if the loop were horizontal. It is thus not truly a siphon, but if such a *siphon-like mechanism* were operating in the anterior vessels of an upright animal, gravity would have no effect on cephalic blood flow and no additional energy would be required to perfuse an elevated brain.

Seymour et al. (1993; R715-716) explored the inverted U tube analogy, describing the siphon-like system as:

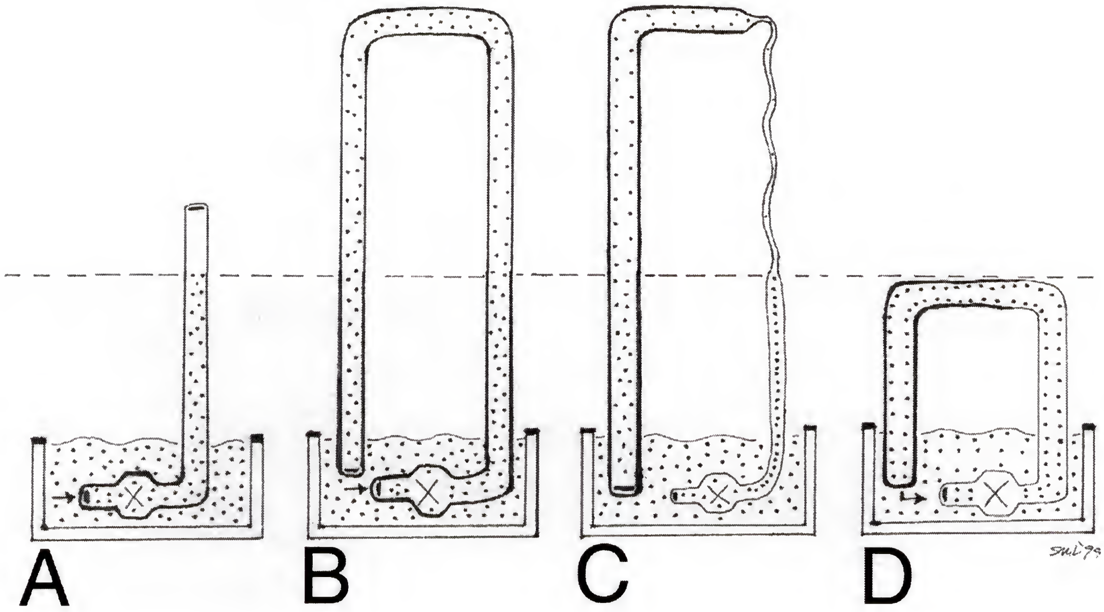
> … a rigid fluid-filled U-shaped tube of any size, cross-sectional shape, or orientation. The only work that is required to move the fluid from one arm to the same level in the other arm is that required to overcome viscous friction of the fluid in the tube. If the length of the tube remains the same and the tube is tilted in the gravitational field, the vertical height of the bend has no effect on the work required to move the fluid. Flow ("siphoning") is not necessary for a siphon to exist. The only requirement is to have equality of the hydrostatic (gravitational) pressure gradient in both arms of the loop. Because these gradients are equal and opposite in direction along the two arms of the tube, no net work is required to move the fluid "uphill" against gravity.

They are careful to note that the conduits must be rigid, capable of withstanding negative internal pressures without collapsing. In a vertical loop, gravity pulls on the liquid and creates a vertical pressure gradient that is increasingly negative moving up both arms of the loop from the liquid surface (Fig. 4.1B). Collapsible conduits cannot support negative internal pressure above the liquid surface and allow the liquid to drain as they collapse. Both arms of a vertical system without continuous flow must therefore be rigid to support the siphon-like system (Seymour et al., 1993), just as the portion of a true siphon that passes above the liquid surface must be rigid and resistant to collapse.

However, I must note that these requirements change in a system with flow where a pump feeds the ascending arm (Fig. 4.2). Under certain circumstances, a siphon-like mechanism can still operate if some of the conduit is collapsible. Pressure in the ascending arm will be positive up to the height where the gravitational pressure from the standing column of liquid has exceeded the pressure output of the pump and liquid ceases to flow. This height is called the standing head (Fig. 4.2A). If the height of the vertical loop is greater than the height of the standing head of the pump (what I here designate a type I siphon-like system), then the same restrictions apply as in a no-flow system (Fig. 4.2B). A collapsible ascending arm would not be able to support the negative internal pressure that would exist between the level of the standing head and the summit (Fig. 4.2C). But, if the standing head is higher than the summit (a type II siphon-like system), the pressure will be positive all the way to the top and the ascending conduit can be collapsible throughout its length (Fig. 4.2D). A type II siphon-like system with a collapsible ascending arm requires flow to maintain siphon-like conditions.

In the circulation of vertebrates adapted to upright posture, the standing head is always above the summit of the circuit. The heart is capable of pumping blood to the head without any assistance from venous return. This must be so, for even if blood supply to and from the structurally supported cranium occurred through rigid conduits and formed a siphon-like system, the blood vessels of the extracranial tissues are not so protected and cannot support negative intraluminal pressure. To perfuse the sensory

FIGURE 4.2. The concept of a standing head and its relationship to conduit rigidity. **A.** The pump is immersed in the reservoir and pushes water up the vertical conduit. Depending on the power of the pump, there is a height at which the gravitational pressure of the superior water column exceeds the output of the pump and flow stops at that level, the standing head. **B.** In a vertical circuit of rigid conduit, water can be made to flow above the standing head because descending water draws up the ascending water behind it. Pressures within the ascending conduit are positive below the standing head and negative above. The conduit must be rigid to support negative internal pressure and prevent collapse, as in **C.** In **D**, the entire circuit is below the standing head, and pressure is positive throughout the ascending conduit. The ascending conduit can be collapsible and the siphon-like effect still operates.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organs and other facial tissues, arterial blood pressure must be positive to the top of the head (Seymour et al., 1993).

In either case, the descending conduit must be rigid for a siphon-like effect to occur. This concept was perspicuously conveyed by a series of models in a paper by Seymour and Johansen (1987), recreated here for discussion (Fig. 4.3). The basic inverted U consists of two rigid 50-cm tubes oriented vertically and connected at their tops by a short and narrow high-resistance tube (Fig. 4.3A). A constant-pressure pump feeds one of the larger tubes, generating 100 cm H_2O pressure and a constant flow rate across the high-resistance connector. Note that the summit (50 cm) is lower than the standing head (100 cm), as in the vertebrate circulation. The larger tubes offer no significant resistance to flow, but the pressure difference across the high-resistance connector is 100 cm H_2O. As in any column of fluid, gravitational pressure gradients develop in the two tubes. Because the summit is less than the height of the standing head, pressures throughout the ascending arm are positive. Liquid in the rigid descending arm develops a gravitational pressure gradient that is equal and opposite to that developed in the ascending conduit. The pressure at the bottom of the return conduit is atmospheric and the top is therefore -50. The pressure drop across the resistor is 100 cm H_2O and the flow rate is constant. Because all conduits are rigid and parallel gravitational pressure gradients exist, a siphon-like mechanism is in operation. If this system were horizontal, the flow rate would be exactly the same.

If we remove the rigid return conduit, liquid falls freely from the open end of the connector back to the reservoir below (Fig. 4.3B). Without the rigid tube and its gravitational pressure gradient, sub-atmospheric pressures do not develop downstream of the connector; the pressure here is atmospheric. Consequently, the driving pressure across the high-resistance connector is halved, as is the flow.

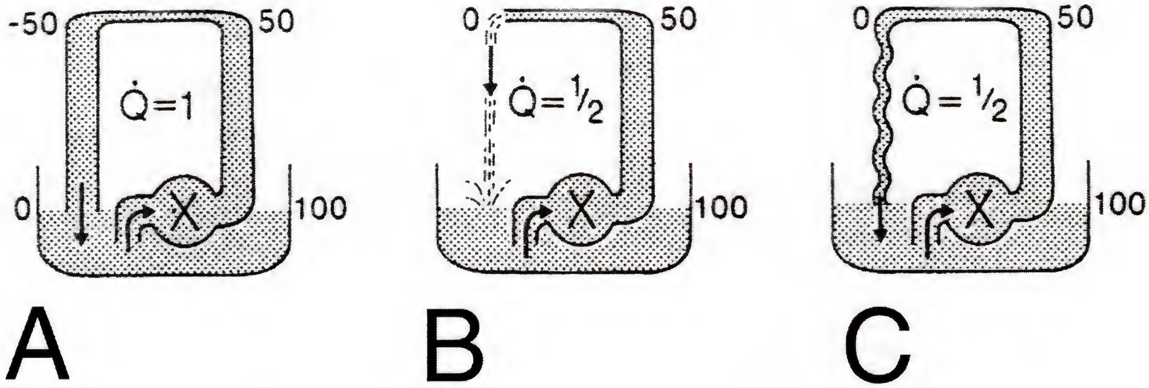
If we replace the rigid return conduit with a collapsible one, the flow remains at 50% (Fig. 4.3C). The collapsible conduit cannot support negative internal pressure: its internal pressure is essentially atmospheric throughout. Thus, the driving pressure remains halved. Liquid simply falls through the partially collapsed conduit at ½ its original rate and "waterfall" dynamics still apply. For liquid descent to affect liquid ascent, the return conduit must be rigid.

Jugular vs. Spinal Veins

It is now apparent that many vertebrates have prominent spinal veins of one form or another encased within the bony vertebral column (chapter 3, and therein). Spinal veins have been documented in most vertebrate clades: chondrichthyans, osteichthyans, amphibians, mammals, chelonians, crocodilians, birds, and squamates (Table 3.2). In some species, the spinal veins take the form of an anastomotic plexus, with several interconnecting, longitudinal vessels coursing within and around the vertebral column. In others, the spinal vein forms one or more voluminous extradural 'sinuses' dorsal, ventral, or lateral to the spinal cord. In sloths and pinnipeds, sections of the caval veins are physically reduced and the spinal veins are normally the only avenue for venous return from certain parts of the body (Wislocki, 1928; Harrison and Tomlinson, 1956).

While they surely evolved for reasons unrelated to circulation in vertical circuits, spinal veins have adopted this role in some terrestrial vertebrates. In those animals that have been examined radiographically (humans, rhesus monkeys, rat snakes, and hatchling

FIGURE 4.3. The role of the descending conduit (modified from Seymour and Johansen, 1987). **A.** A rigid return conduit can support negative internal pressure, allowing the development of an equal and opposite gravitational pressure gradient, and thus a siphon-like effect. **B.** Removing the return conduit makes the system similar to a waterfall. The pressure is now atmospheric at the top, halving the driving pressure and the flow. **C.** Adding a collapsible conduit is no different than having no conduit. The collapsible tube cannot sustain internal pressures less than zero and flow is not facilitated.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Burmese pythons), the vertebral plexus is the primary route of venous return from the head during upright posture (chapter 3 and therein). The jugulars receive little flow and are presumed (and sometimes observed) to be at least partially collapsed. The spinal veins, however, are protected from gravity. They always remain patent by way of extensive periosteal adhesion to the bones of the cranium and vertebral column, thus providing a non-collapsible conduit for venous return that is capable of supporting a gravitational pressure gradient parallel to that in the arteries. As blood passes through the cerebral capillary bed, it moves into the open system of cranial venous sinuses and descends through rigid spinal veins. Although the jugulars do receive some efflux from extracranial tissues, the majority of arterial flow to the head is intracranial and passes from the cranial sinuses into the vertebral plexus. The role of the jugulars in vertical circuits therefore seems relatively unimportant.

Passage of cerebral efflux into the spinal veins has great bearing on the siphon controversy. By allowing the development of a parallel gravitational pressure gradient, the encased spinal veins facilitate cerebral perfusion during upright posture in what can be considered a *partial* siphon-like mechanism. Gravitational pressure gradients develop in the anterior arteries, and cranial arterial pressure can be reduced by as much as 75% without loss of consciousness (Henry et al., 1951). A similar gradient develops in the anterior veins. Negative pressure in the cranial venous sinuses has been calculated (Burton, 1972; Badeer and Rietz, 1979) and directly observed (Dilenge et al., 1975; Guyton and Hall, 1996), and clearly obtains during radial acceleration (Rushmer et al., 1947; Henry et al., 1951). These sinuses feed both the jugular and vertebral plexus veins. However, the jugulars are incapable of supporting negative intraluminal pressures and tend to collapse in upright animals. The vertebral venous plexus, on the other hand, is maintained patent by adhesion to the surrounding bone, and a negative pressure is maintained internally. A collapsed jugular is still capable of receiving flow, however the plexus simply offers a route of greater pressure drop (relative to the jugulars), thereby driving up the perfusion pressure across the brain. As in the models (Fig. 4.3), the nature of the return conduit determines the driving pressure and therefore flow.

To illustrate this point, let us assume that arterial blood reaches the cerebral capillary bed with a pressure of 100 mm Hg. The jugulars are more or less collapsed and cannot support negative intraluminal pressures. Therefore the maximum driving pressure across the capillary bed to the jugulars is 100 mm Hg. The vertebral system, on the other hand, can sustain negative intraluminal pressure. If, for example, the anterior vertebral veins support –100 mm Hg, the driving pressure, and therefore the rate of cerebral perfusion, is effectively doubled. Alternatively, arterial blood supplying a brain that drains into a vertebral plexus could be 100 mm Hg lower in pressure and still produce the same perfusion rate as a similar system drained by jugulars. Blood pressure need only be high enough to reach the head and perfuse extracranial tissues: blood reaching the brain with a pressure just above atmospheric will be drawn across the cerebral capillaries. This is only a *partial siphon-like effect* because a small portion of the cephalic blood is descending in the jugulars and in portions of the plexus outside the vertebral column. The potential energy of this blood is not reclaimed.

The effect of negative pressure is directly demonstrable. Lambert (1945) showed that during radial acceleration to simulate hypergravity, perfusion of the unprotected cephalic tissues failed before intracranial circulation (as evidenced by loss of vision but not consciousness). He could restore vision (the unprotected circulation) in one or both eyes with the application of light suction in a sealed mask over one or both eyes, respectively.

Due to this facilitating effect, the fall of arterial pressure caused by upright posture is partially compensated (i.e., cerebral perfusion is maintained) simply by flow through the patent, low-pressure spinal veins. This compensatory mechanism operates even at hypergravity where postural effects are exaggerated and cerebral arterial pressure approaches zero (Henry et al., 1951). However, the compensation is not perfect and cerebral blood flow drops by approximately 20% in humans (Scheinberg and Stead, 1949; Lassen, 1959), about 9% in rat snakes (Lillywhite and Gallagher, 1985), and to zero in terrestrial vipers (Lillywhite, 1993a) and aquatic sea snakes (Seymour and Lillywhite, 1976; Lillywhite and Pough, 1983). These numbers reflect the ability of the heart to maintain a standing head higher than the cranium, and perhaps also they relate to the percentage of blood descending in unprotected vessels.

Why Are Blood Vessels Collapsible?

Why then are all blood vessels not rigid, such that a full siphon-like mechanism is invoked and energy is conserved? All arteries in the superior circuit, including those supplying the face, scalp, and other extracranial tissues would have to be stiff and rigid. While such a system works well in the xylem of immobile trees, complete rigidity of the arterial system is just impractical for such flexible organisms as vertebrates. Even if natural selection could produce a vessel that is both flexible and resistant to collapse, there are further problems related to the phasic output of the heart. The heart is a discontinuous pump, and as such, it requires some mechanism to convert phasic output into continuous flow prior to entry of blood into the capillaries. In tetrapods, the energy imparted by the ventricle is initially transferred to the elastic elements of the aorta and primary arteries during systole, then recovered during diastole (the Windkessel effect). This phenomenon is readily observed as an arterial pulse. In giraffes, carotid flow 35 cm below the angle of the jaw reaches a peak systolic level of 60 ml/sec and drops evenly to a minimum of 36 ml/sec at the end of diastole (Van Citters et al., 1968). Although flow in the great arteries is somewhat phasic, these vessels serve as a compression chamber, transforming pulsatile cardiac output into continuous flow to the tissue capillary beds (Brecher, 1956). If the arteries were rigid and flow were phasic throughout the entire circuit, a considerable amount of energy would be required just to set the blood in motion after each diastolic period. In the great arteries, total luminal surface area and resistance are relatively small, but in arterioles and capillary beds, these parameters are immense, as would be the energy required to overcome inertia and drive phasic flow at that level. Perhaps the inertial costs that would be associated with complete phasic flow through rigid vessels outweigh the gravitational energy loss of not utilizing a siphon-like mechanism.

The Role of Cerebrospinal Fluid

The cerebrospinal fluid (CSF) makes three contributions to cerebral perfusion; one is only understood when considered in light of the interaction between CSF and venous blood in the vertebral column. The first two are long-term in effect and act to maintain favorable transmural pressures in and continuous efflux from the cranial vasculature. The third is short-term and facilitates cerebral perfusion immediately following assumption of upright posture.

1) The first long-term effect of CSF on cerebral perfusion involves parallel changes in the gravitational pressure gradients in both CSF and the vertical blood vessels. Vertical posture also induces a hydrostatic (gravitational) pressure gradient in the CSF, and a negative pressure is generated in the cranial dura (Rushmer et al., 1947; Bradley, 1970; Rushmer, 1970; Eckenhoff, 1971). Parallel changes simultaneously occur in the superior vascular system, and as cranial blood pressures fall, so too do pressures in the CSF that surrounds the blood vessels. As a result, transmural pressure differences similar to those seen in the supine posture are maintained, and cerebral blood flow continues uninterrupted (Rushmer et al., 1947). Laboratory models in which "CSF" pressure can be manipulated demonstrate that this parallel change is vital: if "CSF" pressure in the rigid "cranium" is above atmospheric, the compliant vessels representing the cerebral capillaries collapse and perfusion of the "brain" ceases (R. Seymour, pers. com.). A similar result obtains in bluefish and rabbits where artificial increases in intracranial (CSF) pressure cause a decrease in cerebral blood flow that is only partially compensated by a subsequent increase in mean systemic arterial pressure (Beiner et al., 1997).

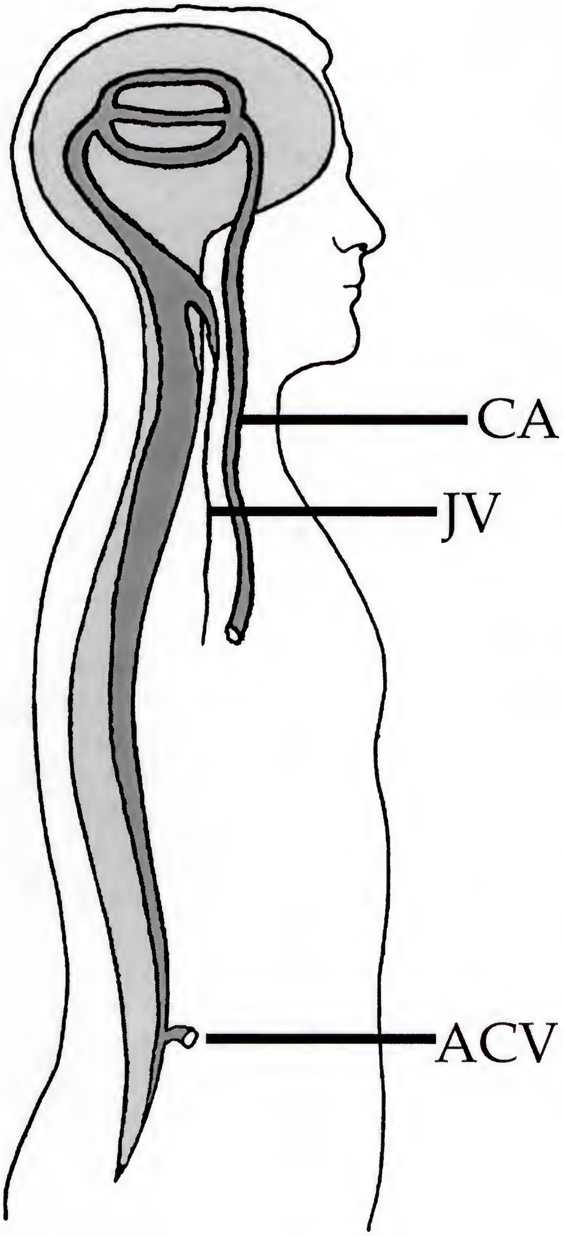
2) The second long-term effect of CSF on cerebral perfusion is slightly subtler. Arterial pulse pressure is not fully dissipated by the Windkessel effect and does reach the cerebral capillary bed, at least in humans. The pulse-coupled increase in volume caused by systolic influx of arterial blood forces a comparable volume of CSF from the skull (Zenker, et al. 1994). This CSF bolus causes a dilation, then elastic contraction of the spinal dura, and presumably a reflux of CSF into the skull during diastole. O'Connell

(1943) observed this phenomenon with every systole and documented a consequent increase in lumbar CSF pressure. One could envision an oscillating system whereby the influx of arterial blood causes an efflux of CSF, which upon its elastically-driven return causes the efflux of a similar volume of venous blood. Interference of this periodic displacement of CSF restricts intracranial arterial expansion resulting in pulsatile venous flow, increased venous flow impedance, and a decrease in cerebral blood flow (Bergsneider et al., 1998).

This effect might be more pronounced in limbless animals, as evidenced by comparative studies of pressure wave contours (Avolio et al., 1982). Intense reflection of pressure waves is seen in stubby-limbed animals, with moderate reflection in those with long tapered limbs. The intensity of reflection is related to the distribution of peripheral reflecting sites, i.e., arterial terminations. In snakes, Avolio and colleagues measured no reflection, and presumably the pressure waves are directed exclusively along the body axis in cranial and caudal directions. However, the influence of these waves on the cranial CSF exchange and cerebral blood flow in snakes and other vertebrates remains to be determined.

3) The short-term effect of CSF on cerebral blood flow is only possible because of the close relationship between the CSF and blood of the spine. The tissues of the central nervous system and the CSF that bathes them are contained within the rigid bones of the cranium and vertebral column. The volume of this bony compartment is relatively unchanging (Monro-Kellie hypothesis) and somewhat larger than that of the nerve tissues and CSF. Much of the remaining space is filled by blood in the venous sinuses of the skull and in the spinal veins of the vertebral column. The amount of each fluid in the

FIGURE 4.4. In the horizontal posture, CSF and vertebral blood are evenly distributed throughout the vertebral column within their conduits, the spinal dura and spinal veins, respectively. During upright posture, CSF and blood are both pulled posteriorly in the column. Blood drains into the abdominal caval veins, and CSF pools in the lumbar dural sac. As blood drains caudally, it is replaced by a similar volume from the cranium, and the spinal veins become engorged anteriorly. ACV, connection to abdominal caval vein; CA, carotid artery; JV, jugular vein, collapsed.


CA
JV
ACV

cranio-vertebral system cannot change, but their distributions can. In the horizontal posture, pressures in the CSF and cranio-vertebral venous systems are approximately equal and fluids in each system are evenly distributed throughout the vertebral column, within their respective conduits (Eckenhoff, 1970, 1971; Nystrom et al., 1998). During upright posture, CSF and blood are both pulled posteriorly in the column. Blood can and does exit the lumbar spinal veins through connections with the abdominal caval veins, but CSF has no such vent: it pools in the lumbar dural sac, further driving the efflux of blood from the lumbar plexus (Reitan, 1941; O'Connell, 1943; Eckenhoff, 1970, 1971; Dilenge and Perey, 1973) (Fig. 4.4). Furthermore, approximately 1-2 ml of CSF exit the cranium during upright posture (Reitan, 1941; Eckenhoff, 1971). As CSF is redistributed from the cranium and cervical and upper thoracic regions of the column to the lumbar region, a similar volume of blood, drawn primarily from the cranial sinuses, replaces it. Blood is simultaneously aspirated through the cerebral capillary bed into the cranial sinuses to maintain constant volume of the whole compartment. Again, the experiments of Lambert (1945) clearly demonstrate this effect of suction at the anterior end of the arterial blood column. Lambert fashioned a mask that sucked on the eyes and prevented blackout in humans that were radially accelerated to simulate hypergravity. Note that this role of CSF in facilitating cerebral perfusion is transient and ends when a volume of blood equal to that which left the lumbar plexus is aspirated through the capillary bed; the effect is not sustained throughout the duration of upright posture. This brief augmentation of cerebral blood flow may be an important factor in the maintenance of consciousness at the initiation of vertical stance before other compensatory mechanisms are activated (Henry et al., 1951).

CHAPTER 5
FUNCTIONAL MORPHOLOGY OF THE CROCODILIAN SPINAL VEIN AND IMPLICATIONS FOR CIRCULATION IN DINOSAURS.

Background

There is little published information regarding the anatomy of spinal veins in non-mammalian vertebrates, and practically none for crocodilians. Rathke (1866) made reference to the basic anatomy of the spinal vein in an unspecified crocodile, with emphasis on the more accessible connections with the caval veins. Beddard (1905b, 1906b) made several observations and clarifying comments regarding these connections. Neither investigator provided illustrations of the spinal vasculature. Subsequent works on crocodilian vascular anatomy ignore the spinal veins entirely (e.g., Reese, 1914; Chiasson, 1962). Olson et al. (1975), reviewing sites for blood collection from reptiles, radiographically demonstrated a vessel within the cervical vertebrae of *Alligator mississippiensis*. This vessel is clearly the spinal vein but was erroneously referred to as the "internal jugular vein."

Modern techniques such as corrosion casting and angiography allow easy access and observation of these otherwise ensconced vessels (e.g., chapters 2 and 3). Herein, I use these methods to elaborate on previous anatomical descriptions of the crocodilian spinal vein and to reveal blood flow patterns in this vessel during several activities relevant to crocodilian biology. Using this information, I then combine studies of paleontology and neontology to make inferences about circulatory patterns in upright dinosaurs.

Materials And Methods

Juvenile crocodilians of mixed sexes were provided by a local zoo. I housed the animals in glass aquaria or fiberglass tanks set up as aqua-terraria and fed them a prepared alligator chow (Burris Aquaculture Feeds, Franklinton, LA). Acclimation air temperatures were maintained between 24 and 26°C. The Institutional Animal Care and Use Committee of the University of Florida approved all research on these animals.

Resinous casts of the circulatory system were produced as in previous chapters (Table 5.1). Injection sites included the ventral abdominal veins, the jugular veins, the carotid artery, and/or the aortic arches. Stopping the digestion process after the NaOH bath allowed me to study the relationships between blood vessels and bones before I went on to macerate the bone as well. Vascular casts of ratite birds with bones intact were borrowed from a colleague (J. Sedlmayr) and examined.

Animals used for fluoroscopy (Table 5.2) were sedated with 1.0 mg/kg xylazine IM (XYLA-JECT®; Phoenix Pharmaceutical, Inc., St. Joseph, MO) followed after 30 min with 20 mg/kg ketamine hydrochloride IM (Ketaset®; Fort Dodge Laboratories, Inc. Fort Dodge, IA) and 0.01 mg/kg glycopyrrolate IM (Robinul®; A.H. Robins Co., Richmond, VA). After an additional 30 min, animals were generally tractable enough for intubation. They were induced with 5% isoflurane (IsoFlo®; Abbott Laboratories, North Chicago, IL) and maintained at 3%. I prepared a sterile field at various sites along the dorsal midline for catheter insertion and administration of iodinated contrast medium.

Table 5.1. Crocodilian species used for vascular casting.

Species	N	Body Mass (g)	SVL (cm)
Alligator mississippiensis	2	290, 1370	22, 38
Caiman latirostris	7	57 - 66	12 - 14
Crocodylus siamensis	3	60 - 700	14 - 30
Osteolaemus tetraspis	1	31	12

Table 5.2. Data for alligators used in fluoroscopy studies.

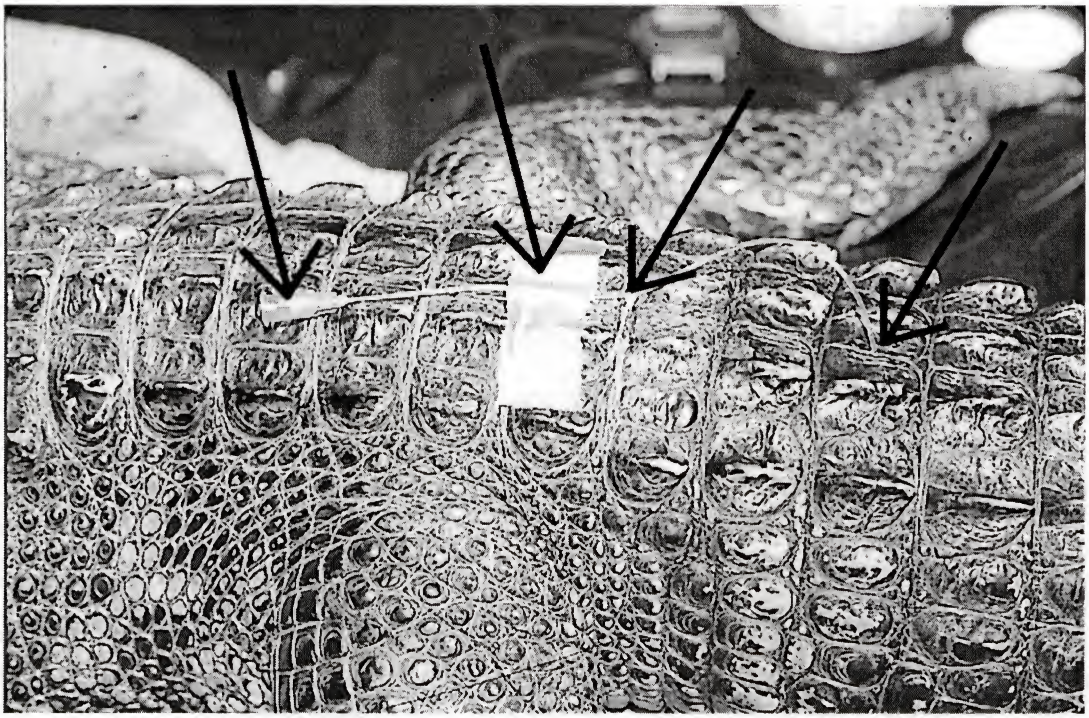
Body Mass (kg)	SVL (cm)	Catheter site*	Treatment
5.2	51	S1-2	air, water
10.3	66	C1-2, Ca3-4	air, heat, water
14.7	78	C1-2, L2-3, Ca3-4	air, heat, water
8.3	65	L2-3, Ca7-8	air, heat
5.1	65	L3-4, Ca9-10	air, heat

* catheter sites between vertebrae; C = cervical, L = lumbar, S = sacral, Ca = caudal

Catheters were introduced into the spinal vein with 18 gauge Seldinger type needles, either a modified Cournand style needle (length = 2 1/16") or a modified Seldinger needle (length = 2 3/4") (Universal Medical Instrument Corp., Ballston Spa, NY). I secured emerging catheters with tissue adhesive and a ligature to the skin (Fig. 5.1). Catheters were then plugged with blocked needles (tissue adhesive in the hub), and flushed periodically with heparinized (2 units/ml) saline (0.9%). Animals were placed in large glass aquaria and allowed at least 24 hr to recover. For injection of contrast medium, I replaced the plug needle with a needle that had the plastic hub removed, i.e., just the metal shaft. This allowed a catheter to be attached to both ends, and in this way the implanted catheter could be extended to reach out of the tank. Blood flow through the spinal vein was fluoroscopically imaged in lateral and dorsal-ventral planes using a C-arm fluoroscope (as in previous chapters) during air-breathing (31 injections in 5 animals), 'voluntary' submergence in a depth of water equivalent to twice the height of the animal (18 injections in 3 animals; see comments in discussion regarding 'voluntary' dives in captive vs. free-ranging animals), and during exposure to radiant heat on the dorsum from a 250 W heat lamp placed 50-100 cm away (39 injections in 4 animals).

Skeletal material of extant crocodilian species was examined in the dissected zoo animals and at the American Museum of Natural History (all museum numbers below refer to AMNH). Vertebrae from a representative specimen of each extant genus were examined for shape of the neural canal and photographed [*Alligator mississippiensis* (43315), *Caiman yacare* (97303), *Crocodylus rhombifer* (78967), *Gavialis gangeticus* (88316), *Melanosuchus niger* (97325), *Osteolaemus tetraspis* (69057), *Paleosuchus palpebrosus* (78976), and *Tomistoma schlegeli* (113078)]. Vertebrae from extant ratite

FIGURE 5.1. *Alligator mississippiensis.* Emerging catheters used in fluoroscopy for the administration of contrast medium were (from right to left) secured at the site of emergence with tissue adhesive, looped over and ligated to the skin, taped to the skin, then plugged with a blunt hypodermic needle with tissue adhesive in the hub. Dorso-lateral view, anterior to the left.



birds were similarly examined and representative specimens were photographed [*Struthio camelus* (1727), *Dromaius novaehollandiae* (1708), and *Rhea americana* (3783)].

Fossil vertebrae representing the major lineages of extinct archosaurs were examined for indications of the shape of the neural canal (phylogeny as in Witmer, 1997). Only original specimens that were free from matrix, possessed clearly visible neural canals with minimal bilateral asymmetry (distortion), and had not had the neural canal bored out for mounting, were characterized for shape of the canal. Representative specimens were examined and photographed, including fossil crocodilians [Eusuchia unident. (2280), the crocodylid *Necrosuchus ionensis* (3219), the alligatorid *Allognathosuchus mooki* (6780), and the thoracosaurids *Holopsisuchus brevispinis* (2200) and *Thoracosaurus neocessariensis* (2548)], thyreophoran ornithiscians [*Euoplocephalus tutus* (5337), *Stegosaurus* sp. (539, 5752)], ornithopod ornithiscians [hadrosaurine indet. (5276, 5426, 5899), *Tenontosaurus telletti* (3014, 3040)], ceratopsian ornithiscians [*Montanoceratops cerorhynchus* (5464), *Triceratops elatis* (5039) and *T. "maximus"* (5040)], theropod saurischians [*Allosaurus fragilis* (666), tyranosaurid indet. (5468)], prosauropod saurischians [*Plateosaurus* sp. (2110)], and sauropod saurischians [*Apatosaurus* sp. (339), *Camarosaurus "leptodirus"* (5763)].

Results

Vascular Casts

The general vascular anatomy of crocodilians has been documented elsewhere (Reese, 1914; Chiasson, 1962); readers should refer to these sources for detailed descriptions of the vessels mentioned below in connection with the spinal vein. Because of the many similarities between crocodilian and avian vascular anatomy, readers are also referred to Baumel (1975, 1988) for the spinal veins of birds.

An extensive occipital sinus covers the dorsal and lateral surfaces of the brain and drains posteriorly through the foramen magnum into a voluminous cervical sinus (Fig. 5.2A,B). These sinuses are clearly derived from fused posterior cerebral veins, which persist as thickened lateral channels. There is a transverse widening at the foramen magnum where the sinuses are confluent and communicate with the jugular vasculature. The cervical sinus continues caudally as the spinal vein, a broad vessel wider than the jugulars that remains dorsal to the neural cord for the entire length of the vertebral column (Fig. 5.2C). A lateral plexus of smaller vessels is present on each side of the cord (Fig. 5.2D).

The spinal vein produces numerous branches throughout its length, dorsally (interspinals), ventrally (basivertebrals), and laterally (intervertebrals). The anterior-most interspinal vein is unpaired and drains the occipital region of the skull and neck caudally into the cervical sinus (Fig. 5.3A). Posterior to this, the interspinal veins usually arise in quartets with two cranial and two caudal branches. The contralateral pairs pass dorsally uniting with their mate before joining the ipsilateral pair, forming a vascular ring between the neural spines in the plane of the longitudinal axis (Fig. 5.3B). A thin longitudinal, subcutaneous vessel (perhaps the homologue of Baumel’s supraspinous vein) joins these circles at their summits where it receives a pair of lateral branches; this arrangement is most prominent in the thoracic spine. Occasionally, however, the interspinal arises again as a single, median, laterally compressed vessel (Fig. 5.3C), as in the occipital region. The interspinal veins are markedly longer in the cervical region where the vertebral

FIGURE 5.2. Vascular casts of crocodilian spinal veins. **A**: *Caiman latirostris*. Full maceration of the head and neck; dorsal view showing the extensive occipital sinus covering the brain. **B**: *Caiman latirostris*. Full maceration of the head and neck; ventral view. **C.** *Crocodylus siamensis*. Partial maceration of vertebral column; ventral view, anterior to the left, vertebral bodies removed. The spinal vein is clearly seen coursing along the dorsal wall of the neural canal. **D.** *Crocodylus siamensis.* Full maceration of vertebral column; lateral view, anterior to the left. Small lateral plexi span the distance between emerging intervertebral veins. AVC, anterior vena cava; IJV, internal jugular vein; IVV, intervertebral vein; LP, lateral plexus; OS, occipital sinus; SV, spinal vein; VB, vasculature of the vertebral body; VV, vertebral vein.

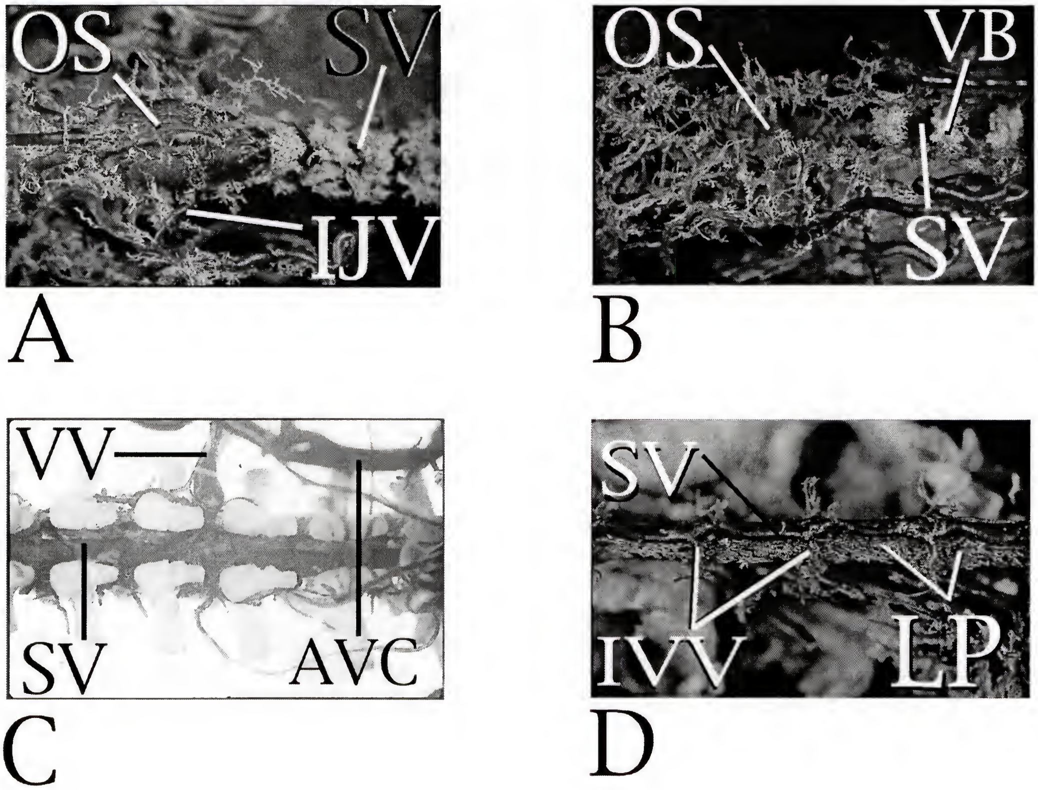
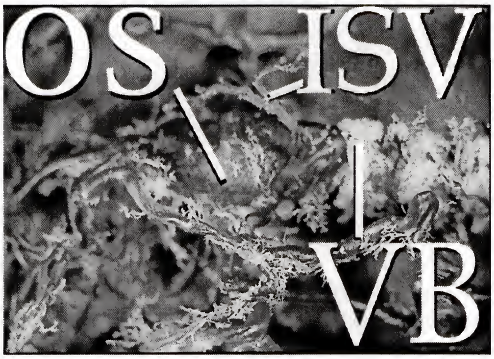
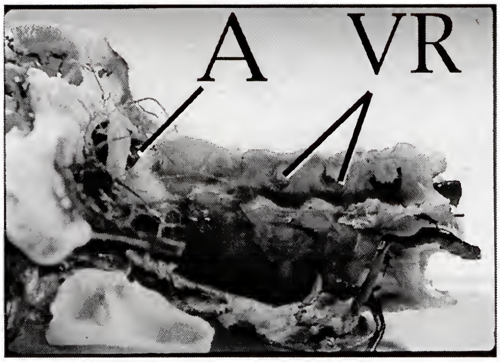

OS
SV
IJV
A
OS
VB
SV
B
VV
SV
AVC
C
SV
IVV
LP
D

FIGURE 5.3. Crocodilian vascular casts. **A.** *Caiman latirostris.* Full maceration of the head and neck; dorso-lateral view, anterior to the left. **B.** *Alligator mississippiensis.* Partial maceration of head and neck; lateral view, anterior to the left. **C.** *Caiman latirostris.* Full maceration of the neck; lateral view, anterior to the left. **D.** *Alligator mississippiensis.* Partial maceration; ventral view of cervical osteoderms. A, atlas-axis junction (for reference); ISV, interspinal vein; OS, occipital sinus; SV, spinal vein; VB, vasculature of the vertebral body; VR, vascular ring.



A



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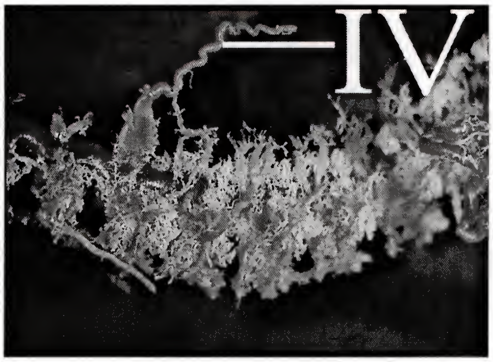
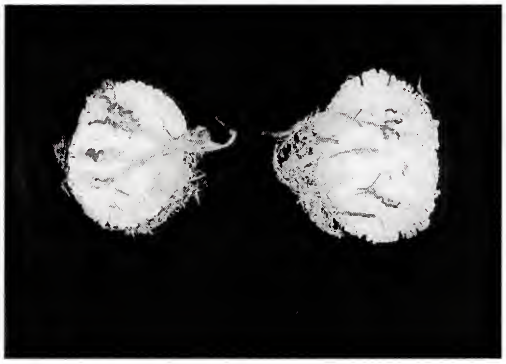


C



D

column curves ventrally and is therefore further from the dorsum. Here, the interspinals form small vascular beds penetrating the ventral surface of the cervical osteoderms (Fig 5.3D).

Two small ventral branches, one per side, are produced at each intervertebral junction (Fig. 5.4A). These vessels pass anteriorly and meet beneath the cord half way to the next junction, giving rise to the basivertebral vein that penetrates the centrum below. This arrangement is most prominent in the cervical region. The basivertebral veins collectively form dense vascular beds that clearly outline the vertebral bodies in the casts (Fig. 5.2A,B, 5.3C, 5.4B).

The lateral branches, or intervertebral veins, arise between each pair of vertebrae. They produce 3 branches: a dorso-cranial branch, which sometimes unites with its serial homologues to form a longitudinal vessel on the dorso-lateral surface of the vertebral column; a ventro-cranial branch that wraps around the vertebral artery; and a lateral branch, which gives rise to the intercostals in the thorax. These vessels collectively form an extensive external plexus in the neck (Fig. 5.3C). Between the third and fourth thoracic vertebrae, the intercostal veins form a pair of large anterior vertebral veins. The vertebrals pass from the vertebral column at the anterior end of the lungs and are equal in magnitude to the anterior caval vein into which they empty (Fig. 5.2C, 5.5A). In some specimens, the vertebral gives rise to anterior and posterior branchlets as it passes from the vertebral column, but these seem to span no more than one segment in either direction. They were not observed to form longitudinal vessels along the column, as observed by Rathke (1866).

Where the spinal vein passes over the liver (thoracic vertebrae 8-12), the intercostal veins form large hepatico-parietal vessels exiting the vertebral column bilaterally (Fig. 5.5B,C). These veins drain the spinal vein into the posterior margin of the liver. The exact number and their point of exit are as variable intra- as interspecifically, and even vary bilaterally in a specimen. The hepatico-parietals generally number one to three per side, sometimes forming longitudinal vessels along the vertebral column, but they usually unite as they pass to and into the liver (Fig. 5.5C). They wrap all the way around the posterior margin, sometimes separating and reuniting with themselves, sending occasional branches into the liver. The hepatico-parietal veins are continuous with ventral abdominal (aka, epigastric) veins on the ventral surface of the liver.

Anastomoses between the spinal and caval veins are essentially segmental posterior to the liver, with some connections more robust than others. The gonads have a large connection, usually bifid, with the spinal vein just anterior to the kidneys (Fig. 5.5D). The ventral abdominal veins are also confluent with the spinal vein immediately thereafter, and the renal vasculature forms a third major axis of communication between caval and spinal veins in the region of the posterior lumbar vertebrae. Between the sacral vertebrae, the pelvic veins form robust connections between the caval veins (where the caudal bifurcates into renal efferents) and the spinal vein; segmental connections between the spinal and caudal vein commence posterior to the sacrum and continue posteriorly (Fig. 5.6).

FIGURE 5.4. Crocodilian vascular casts. **A.** *Crocodylus siamensis.* Full maceration of the cervical vertebral column; ventral view, anterior to the left. Note the paired ventral branches of the spinal veins. **B.** *Caiman latirostris.* Full maceration of the tail; ventrolateral view, anterior to the left. The basivertebral veins form a dense vascular bed outlining the vertebral bodies. CA, caudal artery; CV, caudal vein; SV, spinal vein; VB, vasculature of the vertebral body.

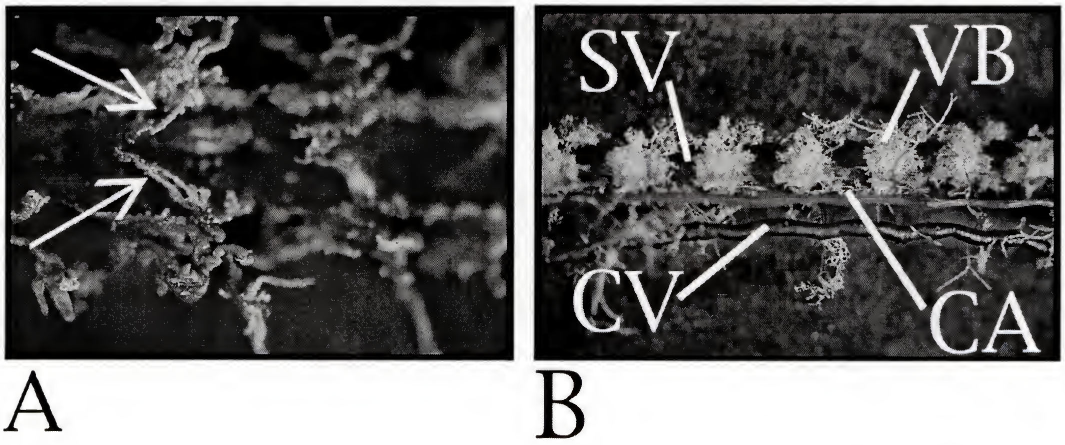

SV
VB
CV
CA
A
B

FIGURE 5.5. *Caiman latirostris*. Vascular casts, full maceration. **A.** Thorax; lateral view, anterior to the left. Some lung casting has been removed to facilitate viewing the vertebral veins. **B.** Thorax/abdomen; dorsal view, anterior down. **C.** Thorax/abdomen; dorsal view, anterior to the left. **D.** Abdomen; lateral view, anterior to the left. AVC, anterior vena cava; G, gonad; HPV, hepatico-parietal vein; K, kidney; Li, liver; Lu, lung; SV, spinal vein; VV, vertebral vein.

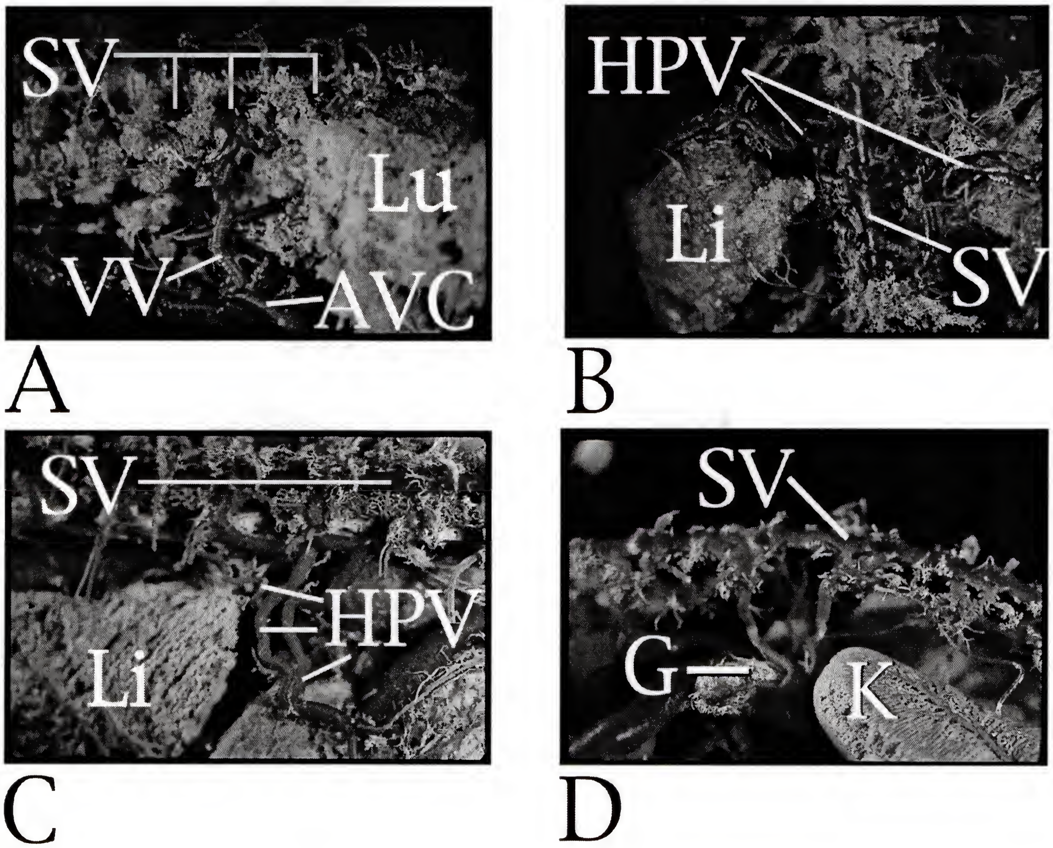
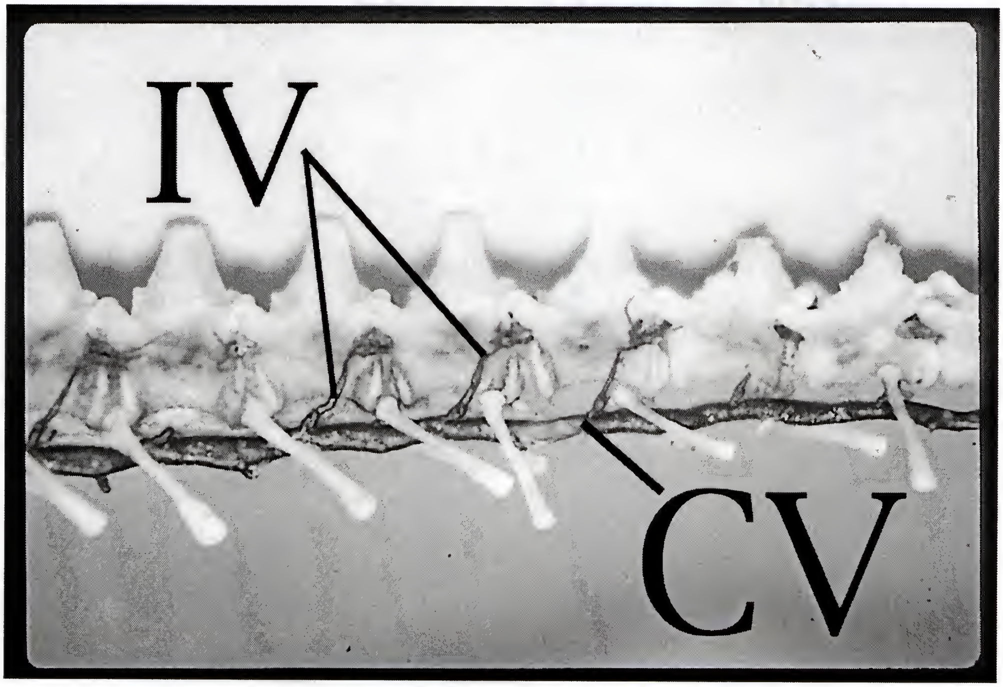

SV
Lu
VV
AVC
A
HPV
Li
SV
B
SV
HPV
Li
C
SV
G
K
D

FIGURE 5.6. *Crocodylus siamensis.* Vascular cast of tail, partial maceration; lateral view, anterior to the left. Segmental intervertebral veins connect the caudal vein to the spinal vein. CV, caudal vein; IV, intervertebral veins.


IV
CV

Fluoroscopy

Contrast medium in the cervical spinal vein (18 injections) always flowed caudally, regardless of treatment, and passed out into the vertebral veins anterior to the heart and into the hepatico-parietal veins above the liver. In air, medium injected in the lumbar spinal vein (nine injections) flowed cranially to the hepatico-parietal veins, but in two injections it flowed as far cranial as the anterior vertebral veins. In the sacral region (four injections), medium in the spinal vein flowed no more than one or two segments longitudinally before passing out the pelvic veins into the ventral abdominal veins. Medium in the caudal spinal vein flowed cranially to the hepatico-parietal veins (13 injections), but four of those times also into the caudal vein via the intervertebral veins, where it continued anteriorly into the ventral abdominal veins.

Submergence in water caused few changes to the pattern seen in air. Medium in the lumbar spinal vein still flowed cranially to the hepatico-parietal veins, but a considerable amount flowed through the segmental intervertebral veins and into the ventral abdominal veins (two injections). In the sacral region, contrast medium again flowed right through the pelvic veins and into the ventral abdominal veins (three injections). Medium injected into the caudal spinal vein (six injections) again flowed cranially to the hepatico-parietal veins, often (three injections) passing also into the caudal vein and continuing anteriorly.

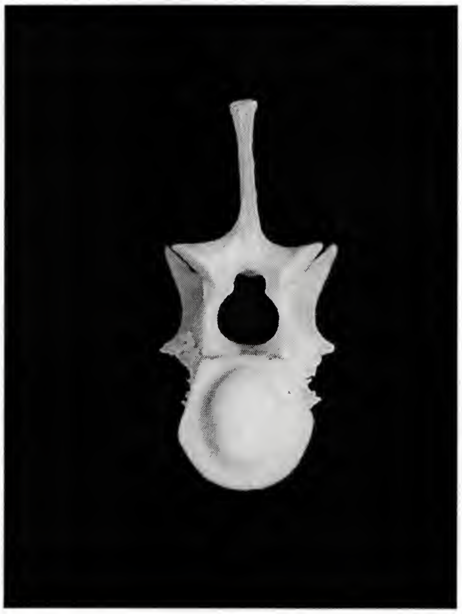
The application of radiant heat to the dorsum caused more considerable changes. When the heat source was directed over the abdomen, medium in the lumbar region flowed cranially as in air, but with more emphasis on passage of blood into the ventral abdominal veins via the intervertebral veins (eight injections). In one case, blood flow was reversed, passing caudally in the spinal vein out the pelvic veins and into the ventral abdominal veins where it then continued anteriorly. Heat over the abdomen also caused changes in blood flow in the tail. Half the time blood flowed caudally (three injections, one animal), and half the time it flowed cranially (three injections, another animal) in the spinal vein, passing out into the caudal and into the pelvic veins, both of which empty into the ventral abdominal veins.

Moving the heat source to a position over the tail, I found that medium in the lumbar spinal vein flowed cranially as in air (seven injections), but in two cases (one animal), blood flow was reversed, passing caudally in the spinal vein out the pelvic veins and into the ventral abdominal veins where it then continued anteriorly. Caudal heat also changed caudal blood flow. Contrast in the caudal spinal vein flowed cranially (seven injections), partially filling the caudal vein as often as not, yet in one instance returning primarily through the caudal vein, and in either case, draining into the ventral abdominal veins at the pelvis. However, in six injections, contrast flowed caudally in the spinal vein as many as seven segments before passing into the caudal vein and flowing anteriorly.

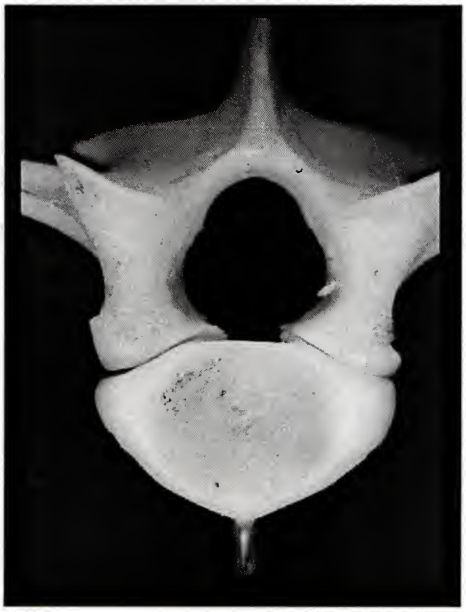
Vertebral Morphology

In all crocodilian specimens examined, extant and extinct, an obvious groove was found in the dorsal surface of the neural canal (Fig. 5.7,5.8). The spinal vein lies dorsal to the spinal cord and courses through this groove. The same groove is seen in ratite vertebrae (Fig. 5.9), where the spinal vein also courses dorsal to the cord. In the terminal regions of the tail in birds, the groove is so well developed that the neural canal is nearly divided into two distinct channels (Fig. 5.9C,D).

FIGURE 5.7. Vertebrae of extant crocodilians. **A.** *Paleosuchus palpebrosus.* **B.** *Alligator mississippiensis.*

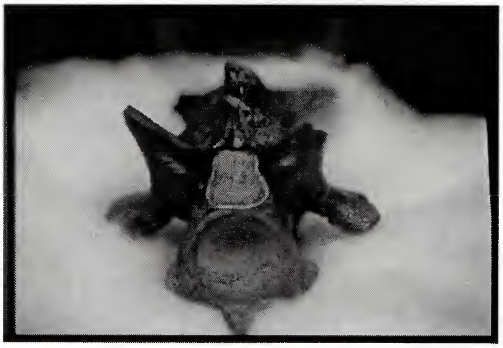


A



B

FIGURE 5.8. Vertebrae of extinct crocodilians. **A.** Eusuchia unident. **B.** *Necrosuchus ionensis.* **C.** *Allognathosuchus mooki.* **D.** *Thoracosaurus neocessariensis.*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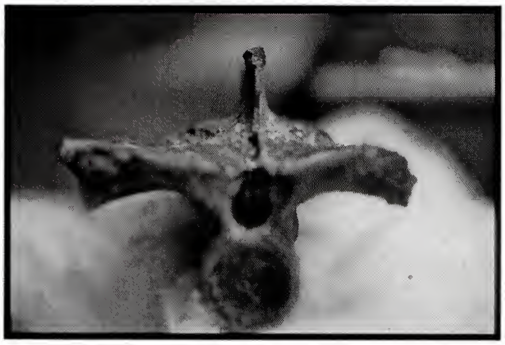
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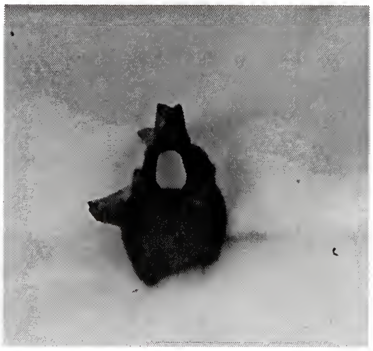

C

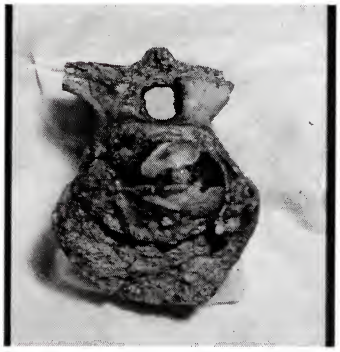
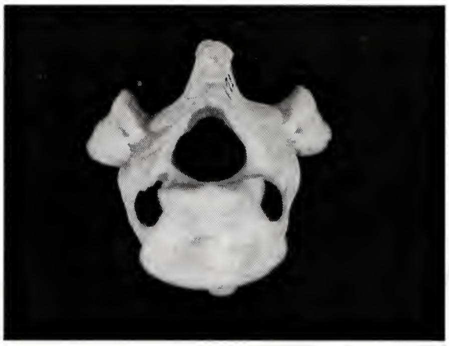
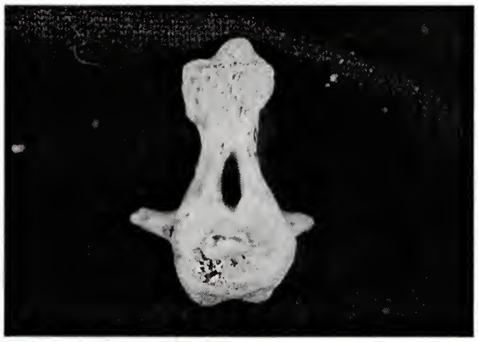

D

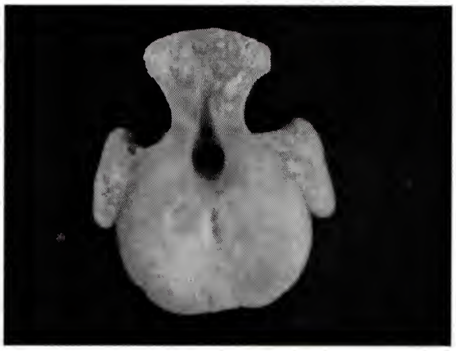
FIGURE 5.9. Vertebrae of extant ratite birds. **A.** *Struthio camelus*, axis. **B.** *Struthio camelus,* sub-terminal caudal vertebra. **C.** *Dromaius novaehollandiae,* sub-terminal caudal vertebra. **D.** *Struthio camelus,* terminal caudal vertebra.



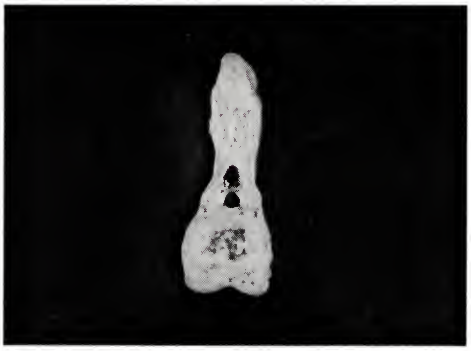
A



B



C



D

In the dinosaurs, dorso-ventral asymmetry of the neural canal was widespread, and often a distinct groove in the dorsal surface of the canal was discernible. Among the thyreophoran ornithiscians (Fig. 5.10), the *Euoplocephalus tutus* material only showed marked dorso-ventral asymmetry (compare to the ostrich in Fig. 5.9B), but the supraspinous groove was clear in *Stegosaurus* sp. Both ornithopod ornithiscians exhibited dorso-ventral asymmetry with a groove (Fig. 5.11). In the ceratopsian ornithiscians, both *Triceratops* species exhibited an obvious groove (Fig. 5.12) that was also evident in *Montanoceratops*. The theropod saurischian material was not in the best condition, but in both *Allosaurus fragilis* and an indeterminable tyranosaurid, dorso-ventral asymmetry was clear (Fig. 5.13). Such was also the case for the prosauropod saurischian *Plateosaurus* sp. (Fig. 5.14). A caudal vertebra of the sauropod saurischian *Apatosaurus* sp. (Fig. 5.15A) showed dorso-ventral asymmetry nearly identical to that seen in the caudal vertebra of the ostrich (Fig. 5.9B), and a supraspinous groove was evident in the thoracic vertebra of the sauropod *Camarosaurus "leptodirus"* (Fig. 5.15B).

Discussion

Spinal veins appear to be a trait common to most if not all extant vertebrates (reviewed in chapter 3). These vessels are an important component of the cervico-cephalic circulation in upright primates and snakes, in which they form a vertebral plexus and appear to facilitate cerebral perfusion. Spinal veins in mammals also serve as a collateral route of venous return to the heart after occlusion or ligation of various veins in the caval system and during transient increases in thoraco-abdominal pressure. Indeed, spinal veins appear to be the only route of venous return from the brain of pinnipeds and from the posterior extremities of sloths (Wislocki, 1928; Harrison and Tomlinson, 1956). Cursory studies have indicated the presence of a well developed spinal vein in crocodilians (Rathke, 1866; Beddard, 1905b, 1906b; Olson et al., 1975). I have demonstrated that the crocodilian spinal vein, although historically overlooked, is as robust as in birds and serves as a collateral route for venous return to the heart. Furthermore, examination of the physical relationships between the spinal veins and vertebrae in extant archosaurs, complemented with details of vertebral morphology in representative extinct archosaurs, allow me to make inferences about vascular anatomy and circulatory patterns in dinosaurs.

Comparisons with Birds

Birds also possess a robust spinal vein that is equally if not more developed than the jugular system (Richards, 1968; Baumel, 1975, 1988; KCZ, pers. obs.). The avian spinal vein also originates from expanded venous sinuses at the base of the skull and extends caudally, dorsal to the spinal cord, to the hip joints (Baumel, 1975). However, there is a diastema in the spinal vein within the lumbo-sacral vertebrae in birds where the spinal cord is enlarged and gives rise to a plexus of nerves, but the vein is continuous cranial and caudal to this point (Baumel, 1988). As in crocodilians, the spinal vein accepts the intersegmental veins throughout its length.

Baumel (1975) stated that blood in the avian spinal vein flows caudally from the head to the base of the neck, where a pair of large vertebral veins drains the spinal vein into the proximal jugulars. He also reported that blood flows cranially from the hip joint

FIGURE 5.10. Vertebrae of thyreophoran ornithiscians. **A.** *Euoplocephalus tutus*. **B.** *Stegosaurus* sp.

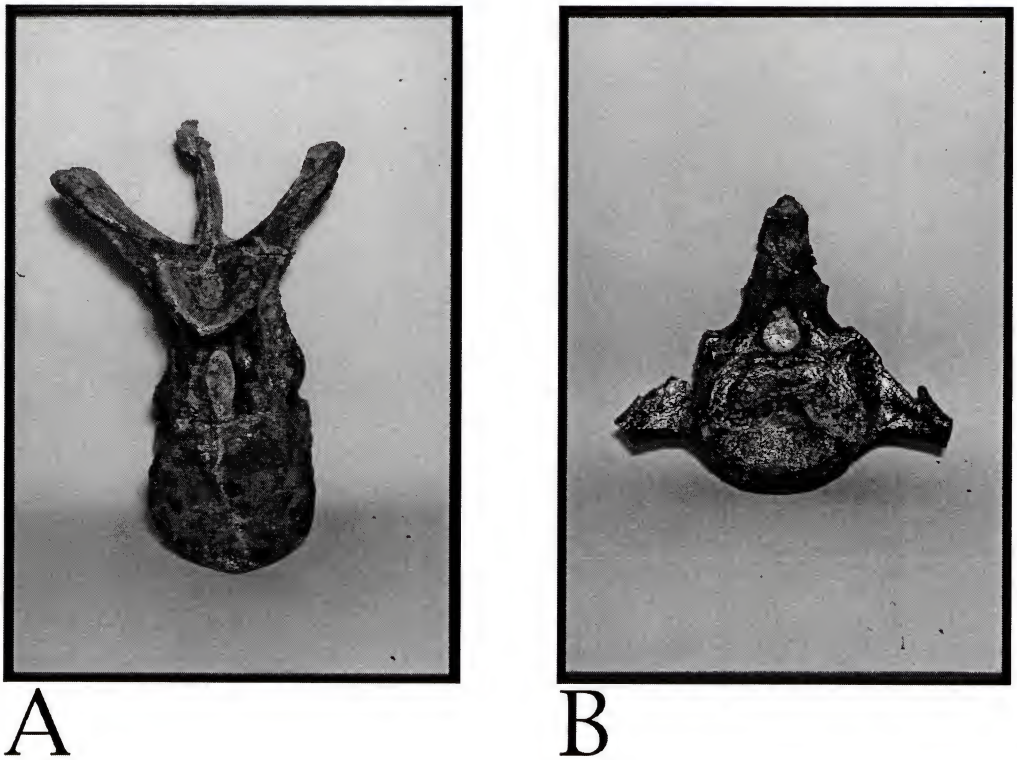
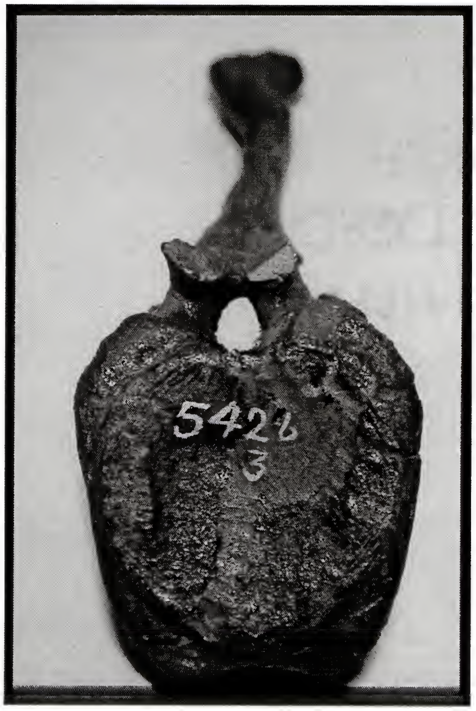
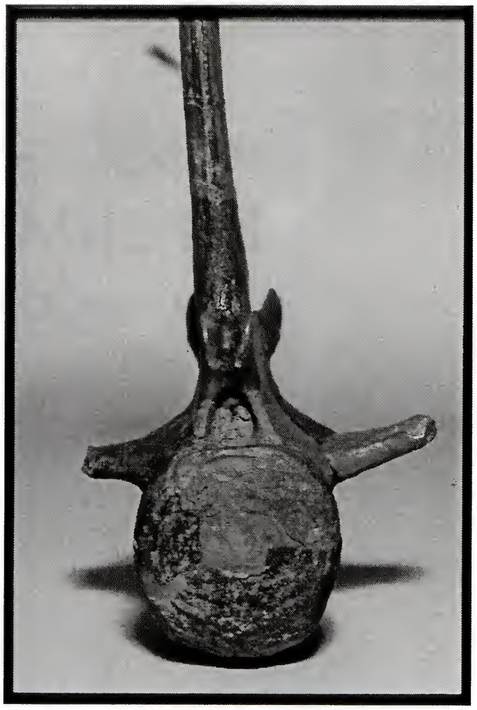

A
B

FIGURE 5.11. Vertebrae of ornithopod ornithiscians. **A.** hadrosaurine indet. **B.** *Tenontosaurus telletti.*

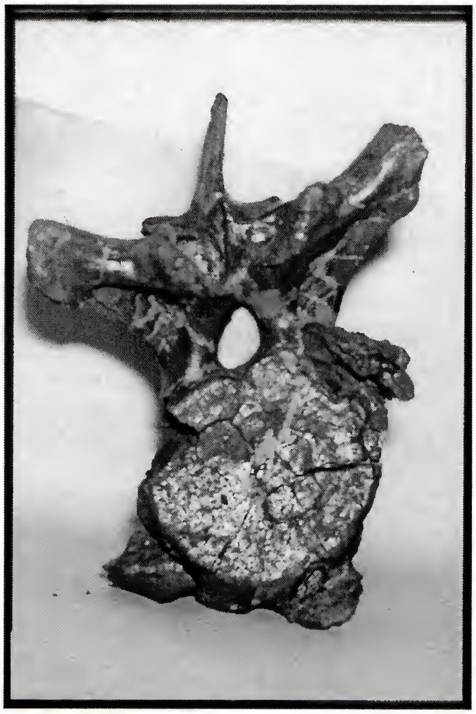


A

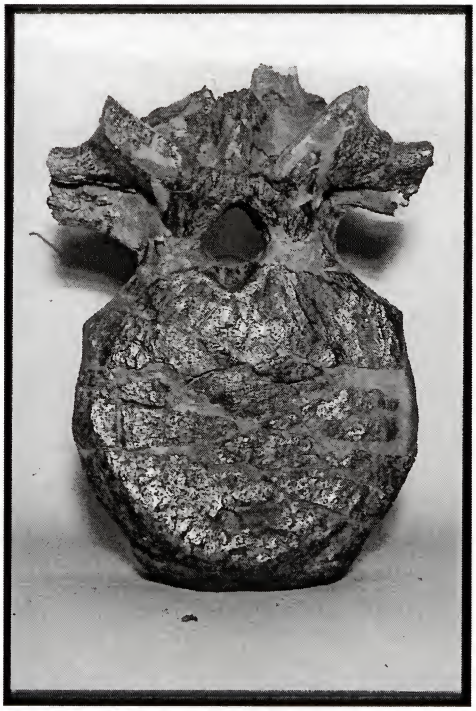


B

FIGURE 5.12. Vertebrae of ceratopsian ornithiscians. **A.** *Triceratops elatis*. **B.** *T. "maximus."*

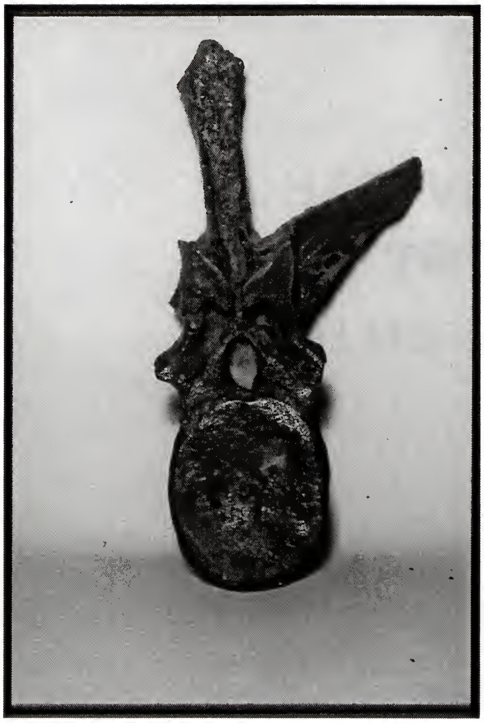


A

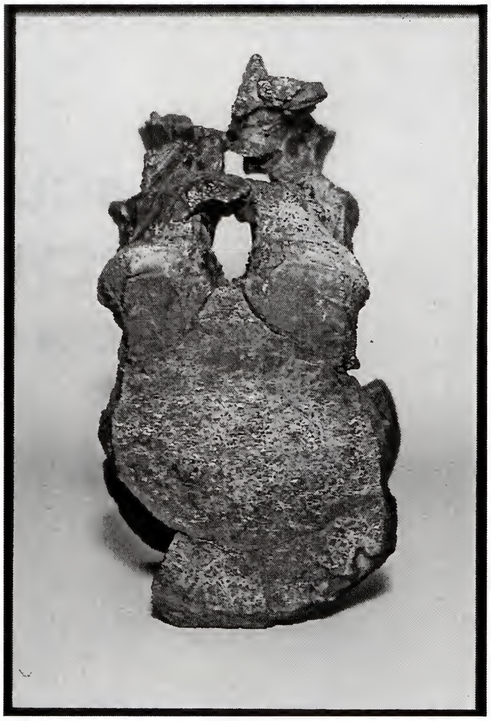


B

FIGURE 5.13. Vertebrae of theropod saurischians. **A.** *Allosaurus fragilis*. **B.** tyranosaurid indet.



A



B

FIGURE 5.14. Vertebra of a prosauropod saurischian, *Plateosaurus* sp.

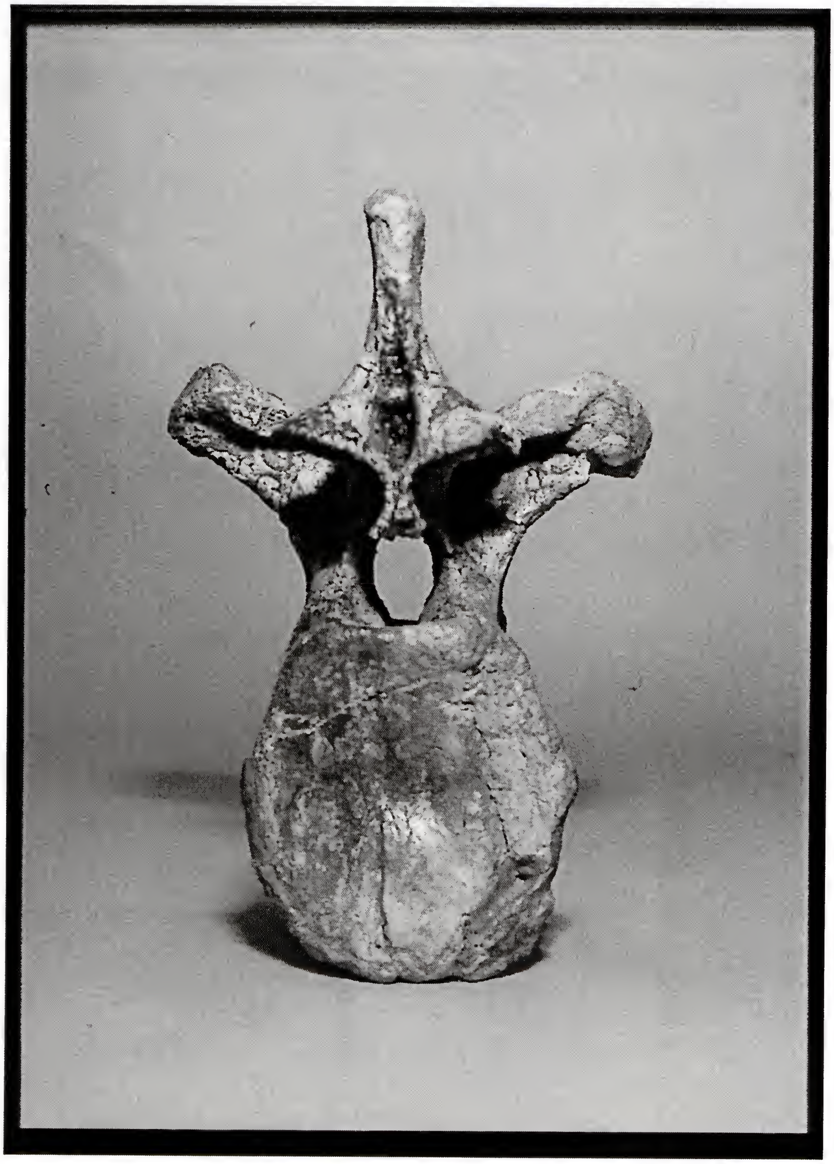
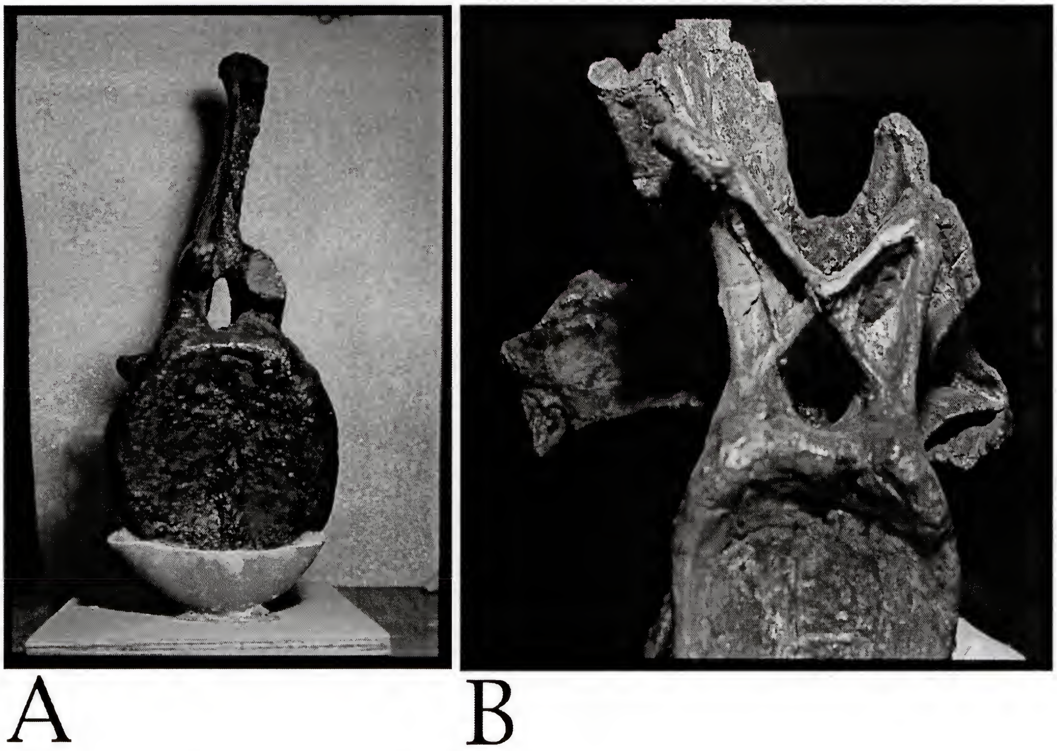


FIGURE 5.15. Vertebrae of sauropod saurischians. **A.** *Apatosaurus* sp. **B.** *Camarosaurus "leptodirus."*


A
B

to the base of the neck and exits the vertebral canal through those same channels. Blood in the caudal spinal vein was reported to flow cranially into the internal iliac veins. It is not stated how Baumel determined the directions of blood flow. This pattern is, however, essentially similar to that seen in crocodilians, except a continuous spinal vein throughout the lumbo-sacral region in crocodilians allows for bi-directional flow in that region, presumably as a function of prevailing pressure gradients. For example, blood from the tail of a crocodilian was observed to reach the heart by flowing cranially through the spinal vein and out the vertebral vein. Under different circumstances, blood in the lumbar spinal vein flowed caudally to exit at the pelvis. Such bi-directionality of flow is rare in vertebrate blood vessels, seen also in the emissary veins in the head of humans (Cabanac and Brinnel, 1985).

Comparisons with Mammals

Non-plexiform spinal veins are extensively developed in some cetaceans and sirenians, and especially in pinnipeds, where the jugular system is poorly developed and drains only extra-cranial tissues (Harrison and Tomlinson, 1956). Venous return through the spinal veins in these animals is thought to facilitate the supply of oxygenated blood to the brain during extended dives (Ronald et al., 1977). In seals, the spinal veins exiting the cranium are paired and lie ventral to the cord in the upper cervical region. These vessels pass laterally around the cord to unite dorsally in the lower cervical region forming a large extradural vessel that extends to the second caudal vertebra (Harrison and Tomlinson, 1956; Ronald et al., 1977). Harrison and Tomlinson (1956) injected contrast medium into the lumbar portion of the spinal vein in an anesthetized seal; contrast passed anteriorly into the cranial sinuses and posteriorly out into the abdominal veins. Blood exiting the cranium of conscious seals passes primarily into the spinal veins and has been radiographically demonstrated to exit through the cervical vertebral venous system, an anastomotic complex of vessels draining the spinal veins into the vertebral veins and anterior vena cava (Ronald et al., 1977). Blood in the thoracic, lumbar, and sacral portions of the spinal vein drains anteriorly into the azygous vein by way of numerous intercostal veins before ultimately passing into the anterior vena cava. The lumbar and sacral portions also share communications with the posterior vena cava.

During a dive, there is a marked restriction of blood flow to all vascular beds except the heart and brain, and there is a reversal of flow in the posterior spinal vein. Blood from the head gradually ceases to flow through the cervical vertebral venous system. Some continues to enter the anterior vena cava by way of the azygous vein, but it accumulates there with little entering the heart. The majority passes instead to the lumbar and sacral regions where it drains into the distal posterior vena cava, and then into a greatly enlarged hepatic sinus where it pushes relatively oxygen-rich blood forward. A caval sphincter at the level of the diaphragm meters out the 'fresh' blood from this reservoir to the heart. In this way, all blood passes through the cerebral circulation once before any is recirculated, and the interventilatory period is extended (Ronald et al., 1977; but see Nordgarden et al., 1998). Some whales can dive for up to two hours (Irving, 1939), and seals for 60 minutes (Elsner et al., 1970).

Crocodilians have also been observed submerging voluntarily for up to 60 minutes (Andersen, 1961). I have found that the anatomy of the spinal veins in crocodilians is convergent on that of diving mammals, with a voluminous spinal vein coursing dorsal to the spinal cord, uninterrupted for the length of the vertebral column. As in diving mammals, crocodilians have been described as having voluminous sinuses around the liver (Rathke, 1866), which in the mammals have been interpreted as a reservoir for oxygenated blood. However, I was unable to detect any consistent and significant changes in circulatory patterns of "diving" crocodilians indicating that they are similarly taking advantage of this vascular arrangement. Circulatory patterns under water were essentially identical to those in air. Although the animals were not forced underwater, the tanks were essentially barren and surrounded by observers manipulating catheters and administering injections of contrast medium. It should be noted that circulatory parameters (e.g., heart rate) observed during non-voluntary dives, and even in voluntary dives during disturbance from man, are considerably different from truly voluntary dives in free-ranging crocodilians (Smith et al., 1974). A similar situation may exist in pinnipeds (Nordgarden et al., 1998). Unfortunately, radiography does not lend itself well to telemetry, and it remains to be determined if blood flow patterns change during undisturbed voluntary dives.

An alternative hypothesis to explain the extent of spinal vein development observed in diving vertebrates suggests that vessels encased in bone are protected from collapse induced by gravity and its effects on transmural pressure. However, the gravitational influence is not via low internal pressures caused by upright posture, but rather by high external pressures that are experienced while diving (Hunter, 1787; Walmsley, 1938). Another hypothesis suggests that voluminous spinal veins might play a role in nitrogen absorption and protection against the bends (Fraser and Purves, 1954).

However, since crocodilians have not been observed diving deeper than 25 m (W. Dunbar, pers. comm.), these explanations seem unlikely for this taxon.

Thermoregulatory Significance

Spinal veins and venous plexi have also been implicated as a vehicle of heat transfer in various mammals (Falk, 1990; Zenker and Kubik, 1996; Rommel et al., 1998). Considering their extensive development in numerous ectotherms, and especially their dorsal location and superficial course around the tissues of the central nervous system, it is conceivable that the hemodynamics through this large vascular bed could significantly affect heating and cooling. Some lizards can alter cutaneous blood flow to facilitate heating and delay cooling (Morgareidge and White, 1969). Cutaneous vasodilation increases the circulation of heated blood from the warm body surface to the body core during heating, while vasoconstriction during cooling maintains that warm blood in the core. More recently, this phenomenon has also been demonstrated in crocodilians (Grigg and Alchin, 1976; Smith 1976; Smith et al., 1978; Robertson and Smith, 1979).

Exposure of crocodilians to radiant heat from above to simulate basking did induce several minor changes in blood flow patterns in the spinal vein. There was a trend toward directing blood flow returning from the posterior extremities away from the spinal vein and over the viscera. In the tail, blood in the spinal vein had a greater tendency to flow caudally. These observations support measurements of the change in regional body temperatures during heating where the tail and viscera heated faster than other parts of the body (Drane et al., 1977). My observations of altered flow patterns could simply be the result of local vasodilation induced by the application of heat (as in Grigg and Alchin, 1976).

It is interesting to note the extensive vascularization associated with the cervical osteoderms. Seidel (1979) described the arterial supply of osteoderms and proposed that these islands of intermingling connective tissues act as thermal collectors in basking crocodilians. The bone and blood absorb heat that is then transferred to the body core through the blood vessels that permeate the bone. Increased arterial flow to the osteoderms during basking has since been verified using infrared cinematography (Discovery's The Ultimate Guide to Crocodiles). The venous vascularization is equally well developed and would certainly allow for increased flow from these structures during basking (Fig. 5.3D). The system might also work as insulation during cooling, as dermal vasoconstriction would keep the heated blood beneath the barrier of bony skin (Seidel, 1979). Unfortunately, the radiographic techniques available to me do not allow resolution of blood flow patterns at this fine level.

Inferences About Dinosaur Circulation

The presence of a spinal vein

I have found that crocodilians possess a robust spinal vein dorsal to the cord, a character shared with birds. The possibility that this character is common to all archosaurs is intriguing. Spinal veins play a major role in the postural hemodynamics of other vertebrates (chapters 3 and 4), and long-necked and upright dinosaurs present an even grander example of gravitational gradients in vertical blood circuits (Millard et al., 1992; Badeer and Hicks, 1996). Biologists have traditionally been challenged to make meaningful statements regarding soft anatomy and physiology in extinct animals, relying on assumption and speculation: "... the exact [cardiovascular] values and specific adaptations of sauropods will never be known and inferences concerning their physiology must rest heavily upon assumptions." (Hohnke, 1973), and "... soft tissues are not preserved as fossils, so we can only speculate on, and not reconstruct ..." details of the cardiovascular system (Choy and Altman, 1992).

Witmer (1995), on the other hand, devised a powerful tool (Extant Phylogenetic Bracketing or EPB) to make reasonable inferences about non-fossilized characters in extinct taxa using our knowledge of the relationships between soft and bony tissues in closely related extant taxa. This process employs basic principles of cladistic phylogenetics, such as outgroup comparison and parsimony, in conjunction with traditional techniques like comparative anatomy. The first step in an EPB analysis is to determine causal associations between soft and hard tissues in the bracketing extant groups. In this case, birds and crocodilians are the closest related extant taxa to dinosaurs and serve as the bracketing groups. Vertebrae from animals in both groups are characterized by a distinct dorsal-ventral asymmetry, such that a pronounced groove exists along the length of the dorsal surface of the neural canal (Fig. 5.7,5.9). Dissections of bird and crocodilian cadavers and casts with bones intact have revealed that the spinal vein courses through this groove dorsal to the spinal cord. The association between the vein and the groove is clear, but in this case, causation is assumed. It is generally accepted that bones are highly influenced by their epigenetic systems and are thus the product of associations with the soft tissues they interact with developmentally (Witmer 1995). For example, enucleation of an eye in an infant will radically alter the development of the facial bones, which are no longer influenced by the physical presence and muscular exertion of the organ (Taylor, 1939). Ontogenetic studies of vertebral development in birds and crocodilians in which the spinal vein had been obliterated at an early stage could address this issue more directly, but seem unnecessary. If we consider the problem phylogenetically rather than ontogenetically, we observe that the location of the vein in different taxa seems to have a clear effect on the morphology of the canal. In primates and snakes, the spinal veins form a ventral plexus and the neural canal is expanded in that region and rounded dorsally (Fig. 5.16; see also Fig. 3.4).

Step two of the EPB analysis involves forming a hypothesis about the condition in the common ancestor of the extant taxa. In this case, I hypothesized that the similarities in the bone/blood vessel associations between the two extant groups are due to inheritance from their common ancestor (Fig. 5.17). The common ancestor must have had a robust spinal vein that was situated dorsal to the spinal cord and grooved the dorsal surface of the neural canal, and the associations observed in the extant taxa are therefore homologous.

Step three involves testing the hypothesis by surveying other descendents (the extinct taxa) of that common ancestor for the presence of the osteologic correlate, the supraspinous groove. In my case, the groove seems to be a character common to all the major dinosaur lineages, and its presence in the extant taxa is therefore indicative of homology, not convergence. Because the two extant taxa possess both the soft tissue suspected to occur in the extinct taxon and the osteologic correlate, the inference is decisive and positive, a level I inference, the most robust possible (Witmer, 1995). I can therefore infer with confidence that a voluminous spinal vein situated dorsal to the spinal cord is characteristic of all archosaurs, including dinosaurs.

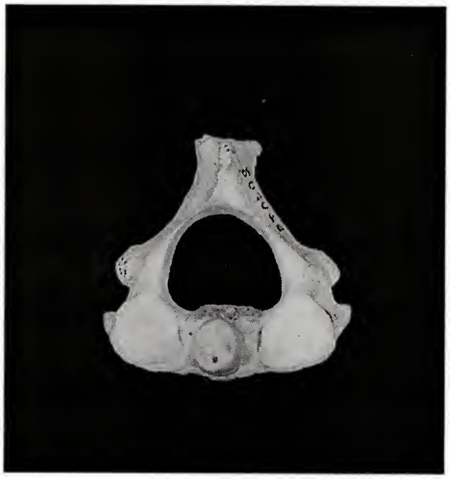
The problem of perfusing an elevated head

Traditionally, sauropod dinosaurs have been regarded as semi-aquatic behemoths, using the buoyancy of water to support their great bulk. However, more recent scrutiny of their skeletal form and footprints suggests a terrestrial existence with an erect stance (Bakker, 1971; Coombs, 1975; Dodson, 1990; Taylor, 1992). These long-necked dinosaurs might therefore represent the extreme extent of vertical blood columns, depending on their posture. The classic view of sauropods depicts them as carrying the head at the level of the body. However, some authors have envisioned them carrying the head perched atop an erect neck 8 vertical meters above the heart in animals standing quadrupedally, and perhaps as many as 12 m above the heart in animals foraging bipedally (Bakker, 1971; Choy and Altman, 1992). Several hypotheses have been offered to address the physiologic challenge of perfusing a brain at these great heights.

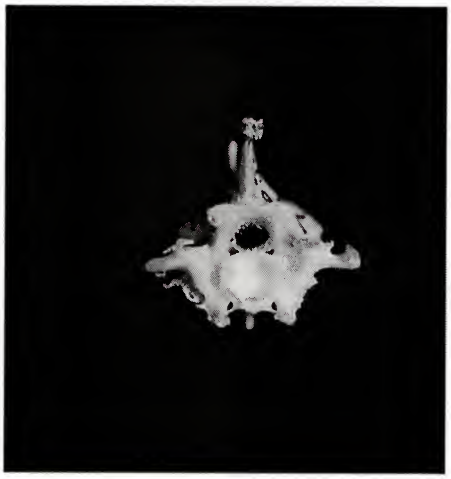
1) The first involves an extrapolated estimate of the ventricular pressure that would be required to raise a fluid column to a particular vertical height. Perfusing the elevated head of quadrupedal (8m) and bipedal (12m) barosaurs would have required 740 and 880 mm Hg of ventricular pressure, respectively (Choy and Altman, 1992; Millard et al., 1992). Such pressures could only be generated by a nearly 7 ton heart over 2 meters across with walls alone almost a meter thick (Seymour, 1976; Dennis, 1992), which seems impossibly large considering the spatial limitations of the thorax.

2) Dinosaurs might have had multiple hearts up the neck that effectively divided the gravitational pressure gradient between the thorax and head, reducing the pressure

FIGURE 5.16. Vertebrae of taxa with ventral spinal veins and subspinous grooves. **A.** Human (*Homo sapiens*, AMNH 204072). **B.** Indigo snake (*Drymarchon corais*, AMNH 73055). The latter specimen has been cleaned with dermestids and the dura are still intact. Consequently, the venous grooves appear as distinct channels.

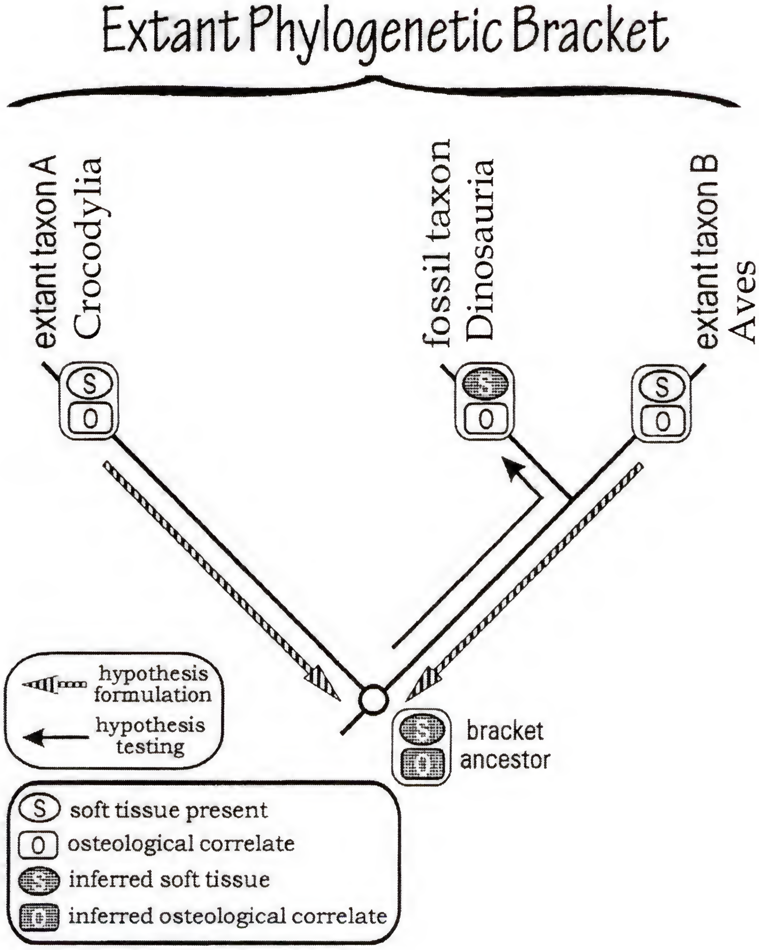


A



B

FIGURE 5.17. The Extant Phylogenetic Bracket approach (modified from Witmer, 1995). Fossil taxa are bracketed by extant taxa. Similar associations between soft and bony tissues in the extant taxa are hypothesized to be homologous, present in the bracket ancestor. The hypothesis is tested by examining the fossil taxa for the osteological correlate, which if present, implies the presence of the soft tissue.


Extant Phylogenetic Bracket
extant taxon A
Crocodylia
fossil taxon
Dinosauria
extant taxon B
Aves
S
O
bracket
ancestor
hypothesis
formulation
hypothesis
testing
S soft tissue present
O osteological correlate
S inferred soft tissue
O inferred osteological correlate

output required of the ‘primary’ heart to approximately 200 mm Hg, less than that of the giraffe (Choy and Altman, 1992; Dennis, 1992). However, such a system is not found in other vertebrates and would clearly be challenged to coordinate the contraction of the multiple hearts and provide continuous flow to the brain (Millard et al., 1992).

3) Extremely low compliance of vessels below the heart might have shifted the gravitational zero pressure from the heart to a point somewhere up in the neck (Badeer and Hicks, 1996). However, regardless of pressure, the heart still must lift the weight of the superior blood column with each contraction, and this shift would not affect the associated workload.

4) A full siphon-like mechanism may have been in effect with negative intraluminal pressures prevailing in the anterior vasculature (Badeer and Hicks, 1996). However, while the hydrodynamics of the cerebrospinal fluid would have protected the cerebral vasculature from collapse, as in other upright tetrapods, this mechanism offers no protection to the extracranial vasculature. Badeer and Hicks (1996) imagine the extracranial vessels enjoying structural support from thickened walls and dense connective tissue attached to a semi-rigid skin. But the blood vessels of the eye could not be so protected, and as Lambert (1945) has shown, perfusion of the unprotected eyes is more posturally sensitive than that of the protected brain. Raising a head 15 m into the trees seems of little value if the leaves to be eaten cannot be seen. And what if the flesh above the standing head were injured? The negative intraluminal pressures proposed (-500 mm Hg) would quickly lead to air embolism and death. There are also concerns

about capillary fluid exchange and the potential for bubble formation in the blood at these highly sub-atmospheric pressures.

The significance of the spinal vein

In previous chapters, I have explored and supported the notion that venous return through spinal veins facilitates cerebral perfusion in primates and snakes. I then reasoned that a spinal vein was also present in dinosaurs. How then would the spinal vein affect a sauropod's ability to stand erect and maintain perfusion of the head? Comparisons of magnitude between the spinal vein and the jugular system in both birds and crocodilians, complemented with fluoroscopic observations of blood flow patterns in the alligator, suggest that the spinal vein is a major route of venous return to the heart in these groups (Richards, 1968; West et al., 1981; this study). In other vertebrates with comparatively less well developed spinal veins, the role of these vessels in venous return from the head becomes greatly exaggerated with the adoption of upright posture. It seems reasonable to assume, therefore, that the dinosaur spinal vein probably served as a major collateral route of venous return to the heart, one that became considerably augmented when the head was raised above the heart. Conceivably, the jugular veins in upright dinosaurs were at least partially collapsed, as they are in numerous upright vertebrates (chapters 3 and 4), and greatly negative pressures were generated in the cranial venous system, increasing the cerebral perfusion pressure and flow.

However, as in other tetrapods (chapter 4), arterial pressure must have been positive up to the head to ensure the perfusion of extracranial tissues. The spinal veins, by providing a drainage route with greatly negative intraluminal pressures, would simply have produced significantly higher flow rates at any given pressure than in a system drained by jugulars (recall the arrangement in Fig. 4.3). A partial siphon-like mechanism was likely operating such that blood reaching the brain was partially pushed through by arterial pressure and partially pulled through by negative pressure in the venous sinuses. In the case of sauropods, I must therefore concur with the conventional view that terrestrial animals probably could not raise their heads and necks completely vertical, at least no higher than their hearts could support (Seymour, 1976; Lillywhite, 1991), *for extended periods of time*. It is possible that the ability of the reptilian brain to tolerate brief periods of hypoxia (Belkin, 1963; Hochachka, 1986) might have allowed these animals briefly to raise their heads into the treetops, just long enough to grab a mouthful of leaves and return to a horizontal posture. Some vertically-tilted snakes continue to exhibit normal behaviors (e.g., head movements, pushing or crawling, and tongue-flicking) well after carotid blood flow has ceased entirely (Lillywhite, 1993a; Lillywhite et al., 1996). However, studies of sauropod morphology and biomechanics also suggest limited abilities of dorsal flexion, revealing instead a wide range of lateral flexion, and a relaxed neck that held the head just above the ground (Alexander, 1985; Stevens and Parrish, 1999). The long necks might have been used for food gathering primarily in the horizontal plane, as is the elephant's trunk (Taylor, 1992). Sauropods antedated angiosperms and lived in a time dominated by fern prairies (Coe et al., 1987; Demko and Parrish, 1998). A long neck would have allowed sauropods to graze over a large area from a fixed point, like "giant, long-necked bovids" (Martin, 1987; Stevens and Parrish, 1999). Or perhaps, as has been suggested for the giraffe, long necks were rarely used for high-browsing, but rather they represent sexual selection for an organ used in male-male combat (Simmons and Scheepers, 1996).

Other dinosaurs, although less spectacular in their potential heart-head distances, might have enjoyed the full postural benefits of the vertebro-spinal veins. Many ornithopods, theropods, and prosauropods had shorter necks but regularly stood erect. Blood flow to the brain of these animals likely returned through and was facilitated by the spinal vein.

CHAPTER 6
SUMMARY

Prior to this study, there was little information available on the vertebral vasculature of reptiles. Regarding arteries, the course of the serpentine vertebral artery had been fairly well traced in a few taxa, but its flow distribution was unknown. Although blood supplying the brain in all vertebrates is carried primarily by the carotid vasculature, cerebral blood flow in most mammals is supplemented by the vertebral arteries, which anastomose with the carotids at the base of the brain. In other tetrapods, cerebral blood is generally believed to be supplied exclusively by the carotid vasculature, and the vertebral arteries are usually described as disappearing into the dorsal musculature between the heart and head. However, there have been several reports of a vertebral artery connection with the cephalic vasculature in snakes. I measured regional blood flows using fluorescently-labeled microspheres and demonstrated that the vertebral artery contributes a small but significant fraction of cerebral blood flow (ca. 13% of total) in the rat snake *Elaphe obsoleta*. Vascular casts of the anterior vessels revealed that the vertebral artery connection is indirect, through multiple anastomoses with the inferior spinal artery, which connects with the carotid vasculature near the base of the skull. Using fluoroscopy and direct observations of flow in isolated vessels, I confirmed that blood in the inferior spinal artery flows craniad from a point anterior to the vertebral artery connections. Such collateral blood supply could potentially contribute to the maintenance of cerebral circulation during circumstances when craniad blood flow in the carotid is compromised, for example, during the gravitational stress of climbing or perhaps during the swallowing of large prey.

The spinal veins of reptiles were essentially unknown. Using corrosion casting, I demonstrated and described a new vascular system – the vertebral venous plexus – in eight snake species representing three families (Boidae, Colubridae, and Viperidae). The plexus consists of a network of spinal veins coursing within and around the vertebral column and was previously documented only in mammals. The spinal veins of snakes originate anteriorly from the posterior cerebral veins and form a lozenge-shaped plexus that extends to the tip of the tail. Numerous anastomoses connect the plexus with the caval and portal veins along the length of the vertebral column. I also revealed a posture-induced differential flow between the plexus and the jugular veins in two snake species with arboreal proclivities. When these snakes are horizontal, the jugulars are observed fluoroscopically to be the primary route for cephalic drainage and the plexus is inactive. However, head-up tilting induces partial jugular collapse and shunting of cephalic efflux into the plexus. This postural discrepancy is caused by structural differences in the two venous systems. The compliant jugular veins are incapable of sustaining the negative intraluminal pressures induced by upright posture. The plexus, however, with the structural support of the surrounding bone, remains patent and provides a low-pressure route for venous return. The vertebral venous plexus is thus an important and overlooked element in the maintenance of cerebral blood supply in climbing snakes and other upright animals. I suspect that this system was previously described (erroneously) as a component of the lymphatic system. My studies of comparative anatomy, histology, and radiography clearly demonstrate that the vessels of the vertebral plexus are veins.

Discovery (or re-discovery) that spinal veins are widespread among reptiles and vertebrates in general sheds new light on the "siphon controversy," an ongoing debate regarding the effects of gravity on cerebral blood supply in upright animals. Some investigators argue that venous descent in the jugulars contributes to a siphon effect, thereby negating any effect of gravity on the ascent of arterial blood. Others reason that a siphon effect can only occur in rigid conduits, and because blood vessels are collapsible, the heart must work against gravity to pump blood to the brain. However, the jugular veins have been directly observed to be at least partially collapsed in humans, giraffes, dogs, and now snakes, and they have been radiographically observed to be inactive in intact, upright animals. Thus, their role in vertical circuits seems irrelevant. Falling intraluminal pressures cannot be supported in the free-standing jugular veins, but adhesion to the bone of the vertebral column maintains patency and negative pressure in the cranial spinal veins. By providing a low-pressure route for cerebral drainage, the spinal veins contribute to a favorable pressure gradient across the brain, driving perfusion and compensating for a posture-induced drop in arterial pressure. CSF plays a significant role in postural hemodynamics, with both short- and long-term effects on cerebral circulation. Re-distribution of CSF within the vertebral column creates a brief suction on the cerebral vasculature and facilitates perfusion, while development of a hydrostatic pressure gradient parallel to that developed in superior blood vessels maintains favorable transmural pressure in the cerebral vasculature.

The ultimate model of blood flow in vertical circuits is in the long-necked dinosaurs. It is estimated that the brain of a barosaur may have been raised to as many as eight vertical meters above the heart. However, without access to soft tissues, what can we possibly say about cerebral circulation in upright dinosaurs? We must, of course, look to extant archosaurs for clues. Although the voluminous spinal veins of birds have been described in detail, little was known of the crocodilian spinal vein. Using corrosion casting, I described the anatomy of this vessel and its connections with the caval veins in four genera. The crocodilian spinal vein arises from an enlarged occipital sinus over the medulla. Unlike in squamate reptiles, the spinal vein is single, voluminous, and situated dorsal to the spinal cord; plexi lateral to the cord span between emerging intercostal veins. These characters are shared with birds. The connections with the caval and portal veins are otherwise similar to those in other tetrapods. I then used fluoroscopy to examine patterns of flow through the spinal vein in alligators. Blood generally flowed longitudinally within the spinal vein toward the heart, draining into the caval veins en route to the heart. Simulation of basking and diving seemed to have little effect on circulatory patterns.

The presence of voluminous spinal veins in both extant archosaur clades suggests such a system might also have been present in dinosaurs. The Extant Phylogenetic Bracket technique allows a rigorous method for drawing inferences about soft anatomy and physiology in extinct vertebrates. I studied the physical relationship between the spinal veins and vertebrae in extant archosaurs to draw inferences about circulatory patterns in dinosaurs. The spinal veins in birds and crocodilians course through a supraspinous channel in the dorsal surface of the neural canal. This channel is also present in certain extinct archosaurs, allowing a level I inference that dinosaurs also possessed a voluminous spinal vein dorsal to the spinal cord. As in other upright vertebrates, passage of cerebral efflux into the spinal veins may have facilitated cerebral perfusion in long-necked and other upright dinosaurs.

Many questions regarding the reptilian vertebral vasculature remain unanswered. Is flow distribution between carotid and vertebral arteries posture sensitive, as it is between the jugular and vertebral venous systems? And if so, is the cerebral contribution of the vertebral artery enhanced by the structural support of the vertebral column? Conducting a microsphere analysis of flow distribution between these two arteries in snakes tilted to 90°, as was done to horizontal snakes in this study, would answer this question.

Does the flow of blood from the head of other vertical reptiles, such as trunk-dwelling anoles and geckos, pass preferentially into the vertebral venous plexus? And what happens when these animals adopt a characteristic head-down position on trees while awaiting prey? Does the posterior portion of the plexus become active? Examining blood-flow patterns in these diminutive reptiles must await the refinement of resolving power in the fluoroscope.

How else is the venous plexus important to snakes? Does it function as a vascular bypass when abdominal masses obstruct the abdominal caval and portal veins, as in mammals? Is it the primary avenue of venous return from the posterior aspects of the body during gestation and after ingestion of large meals? Are the vertebro-spinal arteries protected from occlusion during swallowing of large prey because of structural support from the vertebral column? Again, we must await advancements in the field of fluoroscopy before we can address these questions in snakes in these delicate conditions.

What are the exact gradients of blood pressure up the anterior arteries and down the veins of upright animals, and do they conform to the siphon-like models? Answering this question will require intimate knowledge of both types of vessels going up (vertebral and carotid arteries) and down (jugular and vertebro-spinal veins), the flow distributions between each pair, the extent of their structural support, and the intraluminal pressures within and interstitial pressures around the vessels.

What purpose does the extensive vertebro-spinal system serve in crocodilians? Is it a reservoir for oxygenated blood during extended dives, as has been proposed for pinnipeds and cetaceans? Is it a heat-gathering tissue bed for rapidly raising core body temperatures? Or is it simply a relict from bipedal, terrestrial ancestors? High-resolution telemetry studies of free-ranging crocodilians might address the first two questions.

Why did barosaurs and certain other sauropods have such long necks if not to lift their heads? What anatomical specializations that we are currently overlooking or have yet to discover might have allowed them to do so? These answers must await careful excavation and examination of more sauropod fossils.

The study of vascular structure and function in reptiles is rapidly evolving, primarily as a function of refined technology, but also due to historic, taxonomic bias. I have barely scratched the surface of this topic in a few reptiles, and hopefully this work and further technologic advances will inspire others to delve deeper into the subject, in this and other taxa, both extant and extinct.

LIST OF REFERENCES

Alexander, R.M. (1985) Mechanics of posture and gait of some large dinosaurs. Zool. J. Linn. Soc. London *83*:1-25.

Alexander, R.S. (1963) The peripheral venous system. *In* W.F. Hamilton and P Dow (eds.): Handbook of Physiology. Sect. 2 Circulation, vol. 2. Washington, D.C.: American Physiological Society, pp. 1075-1098.

Andersen, H.T. (1961) Physiological adjustments to prolonged diving in the American alligator *Alligator mississippiensis*. Acta. physiol. Scand. *53*:23-45.

Andersson, B., and P.A. Jewell. (1956) The distribution of carotid and vertebral blood in the brain and spinal cord of the goat. Quart. J. Exp. Physiol. *41*:462-474.

Avolio, A.P., M.F. O'Rourke, B.T. Bulliman, M.E. Webster, and K. Mang (1982) Systemic arterial hemodynamics in the diamond python *Morelia spilotes*. Amer. J. Physiol. *243*:R205-R212.

Badeer, H.S., and J.W. Hicks (1996) Circulation to the head of barosaurs revisited: Theoretical considerations. Comp. Biochem. Physiol. *114A*:197-203.

Badeer, H. S., and J.W. Hicks (1997) Is the flow in the giraffe's jugular vein a "free" fall? Comp. Biochem. Physiol. *118A*:573-576.

Badeer, H.S., and R.R. Rietz (1979) Vascular hemodynamics: Deep-rooted misconceptions and misnomers. Cardiology *64*:197-207.

Bakker, R.T. (1971) Ecology of the brontosaurs. Nature *229*:172-174.

Baldwin, B.A., and F.R. Bell (1963a) The anatomy of the cerebral circulation of the sheep and ox. The dynamic distribution of the blood supplied by the carotid and vertebral arteries to the cranial regions. J. Anat. *97*:203-215.

Baldwin, B.A., and F.R. Bell (1963b) Blood flow in the carotid and vertebral arteries of the sheep and calf. J. Physiol. *167*:448-462.

Baldwin, B.A., and F.R. Bell (1963c) The effect on blood pressure in the sheep and calf of clamping some of the arteries contributing to the cephalic circulation. J. Physiol. *167*:463-479.

Barnett, C.H., R.J. Harrison, and J.D.W. Tomlinson (1958) Variations in venous systems of mammals. Biol. Rev. *33*:442-487.

LIST OF REFERENCES

Alexander, R.M. (1985) Mechanics of posture and gait of some large dinosaurs. Zool. J. Linn. Soc. London *83*:1-25.

Alexander, R.S. (1963) The peripheral venous system. *In* W.F. Hamilton and P Dow (eds.): Handbook of Physiology. Sect. 2 Circulation, vol. 2. Washington, D.C.: American Physiological Society, pp. 1075-1098.

Andersen, H.T. (1961) Physiological adjustments to prolonged diving in the American alligator *Alligator mississippiensis*. Acta. physiol. Scand. *53*:23-45.

Andersson, B., and P.A. Jewell. (1956) The distribution of carotid and vertebral blood in the brain and spinal cord of the goat. Quart. J. Exp. Physiol. *41*:462-474.

Avolio, A.P., M.F. O'Rourke, B.T. Bulliman, M.E. Webster, and K. Mang (1982) Systemic arterial hemodynamics in the diamond python *Morelia spilotes*. Amer. J. Physiol. *243*:R205-R212.

Badeer, H.S., and J.W. Hicks (1996) Circulation to the head of barosaurs revisited: Theoretical considerations. Comp. Biochem. Physiol. *114A*:197-203.

Badeer, H. S., and J.W. Hicks (1997) Is the flow in the giraffe's jugular vein a "free" fall? Comp. Biochem. Physiol. *118A*:573-576.

Badeer, H.S., and R.R. Rietz (1979) Vascular hemodynamics: Deep-rooted misconceptions and misnomers. Cardiology *64*:197-207.

Bakker, R.T. (1971) Ecology of the brontosaurs. Nature *229*:172-174.

Baldwin, B.A., and F.R. Bell (1963a) The anatomy of the cerebral circulation of the sheep and ox. The dynamic distribution of the blood supplied by the carotid and vertebral arteries to the cranial regions. J. Anat. *97*:203-215.

Baldwin, B.A., and F.R. Bell (1963b) Blood flow in the carotid and vertebral arteries of the sheep and calf. J. Physiol. *167*:448-462.

Baldwin, B.A., and F.R. Bell (1963c) The effect on blood pressure in the sheep and calf of clamping some of the arteries contributing to the cephalic circulation. J. Physiol. *167*:463-479.

Barnett, C.H., R.J. Harrison, and J.D.W. Tomlinson (1958) Variations in venous systems of mammals. Biol. Rev. *33*:442-487.

Bartholomew, G.A. (1982) Physiological control of body temperature. *In* C. Gans and F.H. Pough (eds.): Biology of the Reptilia, Vol. 12. London: Academic Press, pp. 167-211.

Batson, O.V. (1940) The function of the vertebral veins and their role in the spread of metastases. Ann. Surg. *112*:138-149.

Batson, O.V. (1944) Anatomical problems concerned in the study of cerebral blood flow. Fed. Proc. *3*:139-144.

Batson, O.V. (1957) The vertebral vein system. Am. J. Roentgenol. *78*:195-212.

Baumel, J.J. (1975) Aves heart and blood vessels. *In* R. Getty (ed.): Sisson and Grossman's The Anatomy of the Domestic Animals, 5th ed., vol. 2. Philadelphia: W.B. Saunders, pp. 1968-2009.

Baumel, J.J. (1988) Functional Morphology of the Tail Apparatus of the Pigeon (*Columba livia*). Adv. Anat. Embryol. Cell Biol. no. 110. Berlin: Springer Verlag.

Beddard, F.E. (1904a) Contributions to our knowledge of the circulatory system in the Ophidia. Proc. Zool. Soc. Lond. *1904*:331-370.

Beddard, F.E. (1904b) Notes upon the anatomy of certain snakes of the family Boidae. Proc. Zool. Soc. Lond. *1904*:107-121.

Beddard, F.E. (1905a) A contribution to the knowledge of the encephalic arterial system in Sauropsida. Proc. Zool. Soc. Lond. *1905*:59-70.

Beddard, F.E. (1905b) Some additions to the knowledge of the anatomy, principally of the vascular system, of *Hatteria*, *Crocodilus* and certain lizards. Proc. Zool. Soc. Lond. *1905*:461-489.

Beddard, F.E. (1906a) Contributions to the knowledge of the vascular and respiratory systems in the Ophidia, and to the anatomy of the genera *Boa* and *Corallus*. Proc. Zool. Soc. Lond. *1906*:499-532.

Beddard, F.E. (1906b) On the vascular system of *Heloderma*, with notes on that of the monitors and crocodiles. Proc. Zool. Soc. Lond.*1906*:601-625.

Beiner, J.M., C.S. Olgivy, and A.B. DuBois (1997) Cerebral blood flow changes in response to elevated intracranial pressure in rabbits and bluefish: a comparative study. Comp. Biochem. Physiol. *116A*:245-252.

Belkin, D.A. (1963). Anoxia: tolerance in reptiles. Science *139*:492-493.

Bergsneider, M., A.A. Alwan, L. Falkson, and E.H. Rubinstein (1998) The relationship of pulsatile cerebrospinal fluid flow to cerebral blood flow and intracranial pressure: a new theoretical model. Acta Neurochir. Suppl. (Wien) *71*:266-268

Blomqvist, C.G., and H.L. Stone (1983) Cardiovascular adjustments to gravitational stress. *In* J.T. Shepherd and F.M. Abboud (eds.): Handbook of Physiology. Sect. 2 The Cardiovascular System, vol. 3. Bethesda, MD: American Physiological Society, pp. 1025-11063.

Bowsher, D.R. (1954) Connections of the internal vertebral venous plexus. J. Anat. *88*:583 (Ab).

Bradley, K.C. (1970) Cerebrospinal fluid pressure. J. Neurol. Neurosurg. Psychiatry *33*:387-397.

Brecher, G.A. (1956) Venous Return. New York: Grune and Stratton.

Brigden, W., S. Howarth, and E.P. Sharpey-Scafer (1950) Postural changes in the peripheral blood-flow of normal subjects with observations on vasovagal fainting reactions as a result of tipping, the lordotic posture, pregnancy and spinal anaesthesia. Clin Sci. *9*:79-91.

Bruner, H.L. (1907) On the cephalic veins and sinuses of reptiles, with description of a mechanism for raising the venous blood-pressure in the head. Amer. J. Anat. *7*:1-117.

Burton, A.C. (1972) Physiology and Biophysics of the Circulation, 2nd ed. Chicago: Yearbook Medical Publishers.

Cabanac, M., and H. Brinnel (1985) Blood flow in the emissary veins of the human head during hyperthermia. Eur. J. Appl. Physiol. *54*:172-176.

Chapman, S.W., and R.E. Conklin (1935) The lymphatic system of the snake. J. Morphol. *58*:385-417.

Chiasson, R.B. (1962) Laboratory Anatomy of the Alligator. Dubuque: Wm. C. Brown Co. Publ.

Choy, D.S.J., and P. Altman. (1992) The cardiovascular system of barosaurs: an educated guess. The Lancet *340*:534-536.

Coe, M.J., D.L. Dilcher, J.O. Farlow, D.M. Jarzen, and D.A. Russell (1987) Dinosaurs and land plants. *In* E.M. Friis, W.G. Chaloner, and P.R. Crane (eds.): The Origins of Angiosperms and Their Biological Consequences. New York: Cambridge Univ. Press, pp. 225-258.

Coombs, W.P., Jr. (1975) Sauropod habits and habitats. Palaeogeogr. Palaeoclimatol. Palaeoecol. *17*:1-33.

Daniel, P.M., J.D.K. Dawes, and M.M.L. Prichard (1953) Studies on the carotid rete and its associated arteries. Phil. Trans. R. Soc. Lond. *237*:173-208.

Davies, D.V. (1947) The cardiovascular system of the slow loris *Nycticebus tardigradis*. Proc. Zool. Soc. Lond. *117*:377-410.

Demko, T.M., and J.T. Parrish (1998) Paleoclimatology – Paleoclimatic setting of the Upper Jurassic Morrison Formation I. Mod. Geol. *22*:1-283.

Dennis, J.M. (1992) Barosaurus and its circulation. The Lancet *340*:1228.

Dilenge, D., and B. Perey (1973) An angiographic study of the meningoarchidian venous system. Radiology *108*:333-337.

Dilenge, D., B. Perey, G. Geraud, and S. Nutik (1975) Angiographic demonstration of the cervical vertebral venous plexus in man. J. Can. Assoc. Radiol. *26*:77-81.

Dodson, P. (1990) Sauropod paleoecology. *In* D.B. Weishampel, P. Dodson, and Halszka Osmólska 9eds.): The Dinosauria. Berkeley: University of California Press, 402-407.

Drane, C.R., G.J.W. Webb, and P. Heuer (1977) Patterns of heating in the body, trunk, and tail of *Crocodylus porosus*. J. Thermal Biol. *2*:127-130.

Dumke, P.R., and C.F. Schmidt (1943) Quantitative measurement of cerebral blood flow in the macaque monkey. J. Physiol. *138*:421-431.

Duomarco, J.L., and R. Rimini (1962) Gradients of pressure in the cardiovascular system. *In* A.A. Luisada (ed.): Cardiovascular Function. New York: McGraw Hill, pp. 167-173.

Eckenhoff, J.E. (1966) Circulatory control in the surgical patient. Ann. Roy. Col. Surgeons, England *39*:67-83.

Eckenhoff, J.E. (1970) The physiologic significance of the vertebral venous plexus. Surg. Gynecol. Obst. *131*:72-78.

Eckenhoff, J.E. (1971) The vertebral venous plexus. Canad. Anaesth. Soc. J. *18*:487-495.

Elsner, R., G.L. Kooyman, and C.M. Drabeic (1970) Diving duration in pregnant Weddell seals. *In* M. Holdgate (ed.): Antarctic Ecology. London/New York: Academic Press, pp. 477-482.

Epstein, H.M., H.M. Linde, A.R. Crapton, I.S. Ciric, and J.E. Eckenhoff (1970) The vertebral venous plexus as a major cerebral venous outflow tract. Anesthesiology *32*:332-337.

Falk, D. (1990) Brain evolution in *Homo*: the "radiator" theory. Behav. Brain Sci. *13*:333-381.

Fawcett, D.W. (1942) A comparative study of blood vascular bundles in the Florida manatee, and in certain cetaceans and edentates. J. Morphol. *71:*105-133.

Francis, E.T.B. (1934) The Anatomy of the Salamander. London: Oxford University Press.

Franklin, K.J. (1937) A Monograph on Veins. Baltimore/Springfield: Charles C. Thomas.

Fraser, F.C., and P.E. Purves (1954) Hearing in cetaceans. Bull. Brit. Mus. (Nat. Hist.) Zool. *2*:101-114.

Ganong, W.F. (1995) Review of Medical Physiology (17th ed.). Los Altos, CA: Lange Medical Publications.

Gauer, O.H., and H.L. Thron (1965) Postural changes in the circulation. *In* W.F. Hamilton and P. Dow (eds.): Handbook of Physiology. Sect. 2 Circulation, vol. 3. Washington, D.C: American Physiological Society, pp. 2409-2439.

Geiger, A., and J. Magnes (1947) The isolation of the cerebral circulation and the perfusion of the brain in the living cat. Am. J. Physiol. *149*:517-537.

Gildea, E.F., and S. Cobb (1930) The effects of anemia on the cerebral cortex of the cat. Arch. Neurol. Psychiat. *23*:876-903.

Gillian, L.A. (1967) A comparative study of the extrinsic and intrinsic arterial blood supply to the brains of submammalian vertebrates. J. Comp. Neur. *130*:175-196.

Goetz, R.H., and E.N. Keen (1957) Some aspects of the cardiovascular system in the giraffe. Angiology *8*:542-564.

Gray, H. (1995) Gray's Anatomy: The Anatomical Basis of Medicine and Surgery (38th ed.). New York: Churchill Livingstone.

Grigg, G.C., and J. Alchin (1976) The role of the cardiovascular system in thermoregulation of *Crocodylus johnstoni*. Physiol. Zool. *49*:24-36.

Groen, R.J.M., H.J. Groenewegen, H.A.M. Van Alphen, and P.V.J.M. Hoogland (1997) Morphology of the human internal vertebral venous plexus: a cadaver study after intravenous Araldite CY 221 injection. Anat. Rec. *249*:285-294.

Guyton, A.C., and J.E. Hall (1996) Textbook of Medical Physiology, 9th ed. Philadelphia: W.B. Saunders.

Harris, H.A. (1964) A note on the clinical anatomy of the veins, with special reference to the spinal veins. Brain *64*:291-300.

Harrison, R.J., and J.D.W. Tomlinson (1956) Observations on the venous system in certain Pinnipedia and Cetacea. Proc. Zool. Soc. Lond. *126*:205-233.

Hasegawa, K., and T. Kubo (1966) Vascular supply in the brain of a snake. Fukuoka Acta Med. *51*:1375-1388.

Henry, J.P., O.H. Gauer, S.S. Kety and K. Kramer (1951) Factors maintaining cerebral circulation during gravitational stress. J. Clin. Invest. *30*:292-300.

Herlihy, W.F. (1948) Experimental studies on the internal vertebral venous plexus. Essays Biol. *1*:151-163.

Heyder, G. (1973) Das Blutgefässsystem von *Typhlops vermicularis* Merram (1820). Gegenbaurs morphol. Jahrb. *119*:492-513.

Hill, L. (1900) On cerebral anemia and the effects that follow ligation of the cerebral arteries. Phil. Trans. Roy. Soc. Lond. B *193*:69-122.

Hill, W.C.O. (1946) Thoracic transpendicular foraminae in the Lorisidae. Proc. Zool. Soc. Lond. *116:*525-530.

Hirabayashi, Y., R. Shimizu, H. Fukuda, K. Saitoh, and T. Igarashi (1996) Soft tissue anatomy within the vertebral canal in pregnant women. Brit. J. Anaesthesia *77*:153-156.

Hochachka, P.W. (1986) Defense strategies against hypoxia and hypothermia. Science *231*:234-241.

Hohnke, L.A. (1973) Haemodynamics in the Sauropoda. Nature *244*:309-310.

Holt, J.P. (1941) The collapse factor in the measurement of venous pressure. Am. J. Physiol. *134*:292-299.

Hunter, J. (1787) Observations on the structure and oeconomy of whales. Phil. Trans. Roy . Soc. Lond. *77*:307-352.

Iijima, T., T. Wasano, T. Tagawa, and K. Ando (1977) A histochemical study of the innervation of cerebral blood vessels in the snake. Cell Tissue Res. *179*:143-155.

Irving, L. (1939) Respiration in diving mammals. Physiol. Rev. *19*:112-134.

Kampmeier, O. (1969) Evolution and Comparative Morphology of the Lymphatic System. Springfield: Charles C. Thomas.

Kashyap, H.V., and S.R. Velankar (1958) The circulatory system of *Natrix piscator piscator* (Schneider). J. Zool. Soc. India *10*:176-194.

Knebel, R. von, and T. Ockenga (1960) Das Verhalten des zentralen Venedruckes beim Kipptischversuch. Z. Kreislaufforschung *49*:235-250.

Kornienko, V.N., and V.S. Shubin (1978) Effect of body position on cerebral circulation in neurosurgical patients. Zh. Vopr. Neirokhir. *4*:25-31.

Lake, A.R., I.J.M. Van Niekerk, C.G.J. Le Roux, T.R. Trevor-Jones, and P.D. Dewet (1990) Angiology of the brain of the baboon *Papio ursinus*, the vervet monkey *Cercopithecus pygerythrus*, and the bushbaby *Galago senegalensis*. Am. J. Anat. *187*:277-286.

Lambert, E.H. (1945) The physiologic basis of "blackout" as it occurs in aviators. Fed. Proc. *4*:43.

Lametschwandtner, A, U. Lametschwandtner, and T. Weiger (1984) Scanning electron microscopy of vascular corrosion casts – Technique and applications. Scan. Electron Microsc. *1984(2)*:663-695.

Lassen, N.A. (1959) Cerebral blood flow and oxygen consumption in man. Physiol. Rev. *39*:183-238.

Lillywhite, H.B. (1987) Circulatory adaptations of snakes to gravity. Am. Zool. *27*:81-95.

Lillywhite, H.B. (1991) Sauropods and gravity. Nat. History *100*:33.

Lillywhite, H.B. (1993a) Orthostatic intolerance of viperid snakes. Physiol. Zool. *66*:1000-1014.

Lillywhite, H.B. (1993b) Posterior-to-anterior shunt of systemic arterial blood flow during head-up posture in arboreal snakes. FASEB J. *7*:A677.

Lillywhite, H.B. (1993c) Subcutaneous compliance and gravitational adaptation in snakes. J. Exp. Zool. *267*:557-562.

Lillywhite, H.B., and J. A. Donald (1994) Neural regulation of arterial blood pressure in snakes. Physiol. Zool. *67*:1260-1283.

Lillywhite, H.B., and K.P. Gallagher (1985) Hemodynamic adjustments to head-up posture in the partly arboreal snake, *Elaphe obsoleta*. J. Exp. Zool. *235*:325-334.

Lillywhite, H.B., and F.H. Pough (1983) Control of arterial pressure in aquatic sea snakes. Am. J. Physiol. *244*:R66-R73.

Lillywhite, H.B., and R.S. Seymour (1978) Regulation of arterial blood pressure in Australian tiger snakes. J. Exp. Biol. *75*:65-79.

Lillywhite, H.B., R.E. Ballard, and A.R. Hargens (1996) Tolerance of snakes to hypergravity. Physiol. Zool. *69*:293-303.

Martin, J. (1987) Mobility and feeding in *Cetiosaurus* (Saurischia: Sauropoda) – why the long neck? *In* P.J. Currie and E.H. Koster (eds.): 4th Symp. Mesozoic Terr. Ecosyst. Short Pap. Tyrrell Mus. Paleontol. Alberta: Drumheller, pp. 154-159.

Melnikov, V.V. (1997) The arterial system of the sperm whale *(Physeter macrocephalus)*. J. Morphol. *234*:37-50.

Millard, W. (1941) The vascular anatomy of *Xenopus laevis* (Daudin). Trans. Roy. Soc. S. Afr. *28*:387-489.

Millard, R.W., H. Baig, and S.F. Vatner (1977) Cardiovascular effects of radioactive microsphere suspensions and Tween 80 solutions. Am. J. Physiol. *232*:H331-H334.

Millard, R.W., H.B. Lillywhite, and A.R. Hargens. (1992) Cardiovascular system design and barosaurs. The Lancet *340*:914.

Morgareidge, K.R., and F.N. White (1969) Cutaneous vascular changes during heating and cooling in the Galapagos marine iguana. Nature *223*:587-591.

Nordgarden, U., L.P. Folklow, and A.S. Blix (1998) Extradural intravertebral venous blood flow in diving harp seals (*Phoca groenlandica*) World Marine Mammal Science Conference Abstracts. p.97.

Nystrom, E.U.M., S.G. Blomberg, and C.W. Buffington (1998) Transmural pressure of epidural veins in the thoracic and lumbar spine of pigs. Anesthesiology *89*:449-455.

O'Connell, J.E.A. (1943) The vascular factor in intracranial pressure and the maintenance of the cerebrospinal fluid circulation. Brain *66*:204-228.

O'Donoghue, C.H. (1912) The circulatory system of the common grass snake, *Tropidonotus natrix*. Proc. Zool. Soc. Lond. *1912*:379-402.

O'Donoghue, C.H. (1914) Notes on the circulatory systems of Elasmobranchs. I. The venous system of the dogfish, *Scyllium canicula*. Proc. Zool. Soc. Lond. *1914*:435-455.

Olson, G.A., J.R. Hessler, and R.E. Faith (1975) Technics for blood collection and intravascular infusion of reptiles. Lab. Anim. Sci. *25*:783-786.

Ottaviani, G., and A. Tazzi (1977) The lymphatic system. *In* C. Gans and T.S. Parsons (eds.): Biology of the Reptilia, Vol. 6, Morphology E. London: Academic Press, pp. 315-462.

Owen, R. (1866) The Anatomy of Vertebrates, vol. 1. London: Longmans, Green, and Co.

Owen, R. (1868) The Anatomy of Vertebrates, vol. 3. London: Longmans, Green, and Co.

Parker, T.J. (1886) On the blood vessels of *Mustelus antarcticus*: A contribution to the morphology of the vascular system in the Vertebrata. Phil. Trans. Roy. Soc. Lond. *1886*:685-732.

Pedley, J.T. (1987) How giraffes prevent oedema. Nature *329*:13-14.

Pedley, T.J., B.S. Brook, and R.S. Seymour (1996) Blood pressure and flow rate in the giraffe jugular vein. Phil. Trans. R. Soc. Lond. B *351*:855-866.

Pritchard, J.A., A.C. Barnes, and R.H. Bright (1955) The effect of the supine position on renal function in the near-term pregnant woman. J. Clin. Invest. *34*:777-781.

Rage, J-C. (1994) Origin and evolution of snakes. *In* R. Bauchot (ed.): Snakes: A Natural History. New York: Sterling, pp. 26-33.

Rathke, H. (1857) Untersuchungen über die Aortenwürzeln und die von ihnen ausgehenden Arterien der Saurier. Denkschr. d. Kais. Akad. d. Wissen. *8*:51-142.

Rathke, H. (1866) Untersuchungen über die Entwickelung und den Körperbau der Krokodile. Braunschweig.

Reese, A.M. (1914) Vascular anatomy of the Florida alligator *Alligator mississippiensis*. Proc. Phil. Acad. Nat. Sci. *1914*:413-425.

Reitan, H. (1941) On movements of fluid inside the cerebro-spinal space. Acta Radiol. *22*:762-779.

Richards, S.A. (1968) Anatomy of the veins of the head in the domestic fowl. J. Zool. Lond. *154*:223-234.

Robertson, S.L., and E.N. Smith (1979) Thermal indications of cutaneous blood flow in the American alligator. Comp. Biochem. Physiol. *62A*:569-572.

Romer, A.S., and T.S. Parsons (1986) The Vertebrate Body (6th ed.). New York: Saunders College Publ.

Rommel, S.A, D.A. Pabst, and W.A. McLellan (1998) Reproductive thermoregulation in marine mammals. Amer. Sci. *86*:440-448.

Ronald, K., R. McCarter, and L.J. Selley (1977) Venous circulation in the harp seal (*Pagophilus groenlandicus*). *In* R.J. Harrison (ed.): Functional Anatomy of Marine Mammals, vol. 3. London: Academic Press, 235-270.

Rowell, L.B. (1993) Human Cardiovascular Control. New York: Oxford University Press.

Rudolph, A.M., and M.A. Heymann (1967) The circulation of the fetus in utero. Circulation Res. *21*:163-184.

Rushmer, R.F. (1970) Cardiovascular Dynamics, 3rd ed. Philadelphia: W.B. Saunders.

Rushmer, R.F., E.L. Beckman, and D. Lee (1947) Protection of cerebral circulation by the cerebrospinal fluid under the influence of radial acceleration. Am. J. Physiol. *151*:355-368.

Savitzky, A.H. (1983) Coadapted character complexes among snakes: fossoriality, piscivory, and durophagy. Amer. Zool. *23*:397-409.

Scheinberg, P., and E.A. Stead, Jr. (1949) Cerebral blood flow in male subjects as measured by the nitrous oxide technique. Normal values for blood flow, oxygen utilization, glucose utilization, and peripheral resistance, with observations of the effect of tilting and anxiety. J. Clin. Invest. *28*:1163-1171.

Schöning, M., and B. Hartig (1996) Age dependence of total cerebral blood flow volume from childhood to adult. J. Cerebral Blood Flow and Metab. *16*:827-833.

Scott, D.B. (1963) Inferior vena caval pressure: changes occurring during anaesthesia. Anaesthesia *18*:135-142.

Secor, S.M., E.D. Stein, and J. Diamond (1994) Rapid upregulation of snake intestine in response to feeding: a new model of intestinal adaptation. Am. J. Physiol. *266*:G695-705.

Secor, S.M., and J. Diamond (1995) Adaptive responses to feeding in Burmese pythons: pay before pumping. J. Exp. Biol.*198*:1313-25.

Seidel, M.R. (1979) The osteoderms of the American alligator and their functional significance. Herpetologica *35*:375-380.

Seymour, R.S. (1976) Dinosaurs, endothermy and blood pressure. Nature *262*:207-208.

Seymour, R.S., and H.B. Lillywhite (1976) Blood pressure in snakes from different habitats. Nature *264*:664-666.

Seymour, R.S., A.R. Hargens, and T.J. Pedley (1993) The heart works against gravity. Am. J. Physiol. *265*:R715-R720.

Seymour, R.S., and K. Johansen (1987) Blood flow uphill and downhill: Does a siphon facilitate circulation above the heart? Comp. Biochem. Physiol. *88A*:167-170.

Simmons, R.E., and L. Scheepers (1996) Winning by a neck: Sexual selection in the evolution of giraffe. Amer. Nat. *148*:771-786.

Slijper, E.J. (1962) Whales. New York: Basic Books, Inc.

Smith, E.N. (1976) Heating and cooling rates of the American alligator, *Alligator mississippiensis*. Physiol. Zool. *49*:37-48.

Smith, E.N., R.D. Allison, and W.E. Crowder (1974) Bradycardia in a free ranging American alligator. Copeia *1974*:770-772.

Smith, E.N., S. Robertson, and D.G. Davies (1978). Cutaneous blood flow during heating and cooling in the American alligator. Am. J. Physiol. *235*:R160-R167.

Stevens, K.A., and J.M. Parrish (1999) Neck posture and feeding habits of two Jurassic sauropod dinosaurs. Science *284*:798-800.

Taylor, M.A. (1992) Barosaurus and its circulation. The Lancet *340*:1228.

Taylor, W.O.G. (1939) Effects of enucleation of one eye in childhood upon the subsequent development of the face. Trans. Ophthomol. Soc. U.K.:*59*:361-371.

Théron, J., and R. Djindjian (1973) Cervicovertebral phlebography using catheterization. Radiology *108*:325-331.

Thompson, J.C. (1914) Further contributions to the anatomy of the Ophidia. Proc. Zool. Soc. Lond. *2*:379-402.

Tomlinson, J.W.D. (1956). Extra-dural vertebral systems in mammals. J. Anat. *90*:575 (Ab).

Van Bourgondien, T.M., and R.C. Bothner (1969) A comparative study of the arterial systems of some New World Crotalinae (Reptilia: Ophidia). Am. Midl. Nat. *81*:107-147.

Van Citters, R.L., W.S. Kemper, and D.L. Franklin (1968) Blood flow and pressure in the giraffe carotid artery. Comp. Biochem. Physiol. *24*:1035-1042.

Vorys, N., J.C. Ullery, and G.E. Handsek (1961) The cardiac output changes in various positions in pregnancy. Amer. J. Obstet. Gynec. *82*:1312-1321.

Walker, W.F., and D.G. Homberger (1992) Vertebrate Dissection (8th ed.). Philadelphia: Saunders College Publ.

Walmsley, R. (1938) Some observations on the vascular system of a foetal female finback. Contr. Embryol. Carneg. Inst. *27*:107-178.

West, N.H., B.L. Langille, and D.R. Jones (1981) Cardiovascular system. *In* A.S. King and J. McLelland (eds.): Form and Function in Birds, vol. 2. London: Academic Press, pp. 235-339

Wislocki, G.B. (1928) Observations on the gross and microscopical anatomy of the sloths. J. Morphol. *46*:317-397.

Witmer, L.M. (1995) The Extant Phylogenetic Bracket and the importance of reconstructing soft tissues in fossils. *In* J.J. Thomason (ed.): Functional Morphology in Vertebrate Paleontology. New York: Cambridge University Press, pp.19-33.

Witmer, L.M. (1997) The evolution of the antorbital cavity of archosaurs: A study in soft-tissue reconstruction in the fossil record with an analysis of the function of pneumaticity. J. Vert. Paleontol. vol. 17, suppl. to no. 1, 73 pp.

Worthman, R.P. (1956a) The longitudinal vertebral sinuses of the dog: I. Anatomical aspects. Am. J. Vet. Res. *17*:341-348.

Worthman, R.P. (1956b) The longitudinal vertebral sinuses of the dog: II. Functional aspects. Am. J. Vet. Res. *17*:349-363.

Youmans, W.B., Q.R. Murphy, J.K. Turner, L.D. Davis, D.I. Briggs, and A.S. Hoye, (1963) The Abdominal Compression Reaction: Activities of Abdominal Muscles Elicited from the Circulatory System. Baltimore: The Williams and Wilkins Company.

Young, B.R., R. Wassersug, and A. Pinder (1997) Gravitational gradients and blood flow patterns in specialized arboreal (*Ahaetula nasuta*) and terrestrial (*Crotalus adamanteus*) snakes. J. Comp. Physiol. B *167*:481-493.

Zenker, W., S. Bankoul and J.S. Braun (1994) Morphological indications for considerable diffuse resorption of cerebrospinal fluid in spinal meninges particularly in the areas of meningeal funnels. Anat. Embryol. *189*:243-258.

Zenker, W., and S. Kubik (1996) Brain cooling in humans--anatomical considerations. Anat. Embryol. *193*:1-13.

Zippel, K.C, H.B. Lillywhite, and C.R.J. Mladinich (1998) Contribution of the vertebral artery to cerebral circulation in the rat snake, *Elaphe obsoleta.* J. Morphol. *238*:39-51.

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Kevin Christopher Zippel was born on 5 April 1972 in Auburn, New York. He attended Union Springs Central High School and in 1994 graduated *magna cum laude* with a Bachelor of Science degree in biology from Cornell University. He immediately matriculated at the University of Florida, and while pursuing his graduate studies, he met Lynn Kirkland and later married her on 20 September 1997. In the fall of 1998 he began a curatorial internship in the Department of Herpetology at the Wildlife Conservation Society / Bronx Zoo. After one year as an intern, he accepted a permanent position at the Detroit Zoo as the Curator of the National Amphibian Conservation Center. In the spring of 2000 he (finally!) completed his dissertation.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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Harvey Lillywhite, Chairman
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